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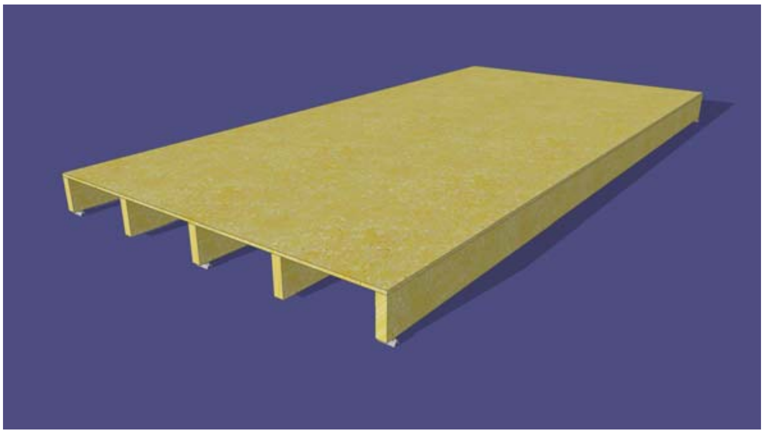

# MEASUREMENTS OF VIBRATIONS IN WOODEN FLOORS INDUCED BY WALKING

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Engineering Acoustics

*Bachelor's Dissertation*

*Department of Construction Sciences*
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# MEASUREMENTS OF VIBRATIONS IN WOODEN FLOORS INDUCED BY WALKING

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# Preface

The work presented in this thesis was carried out in the Division of Engineering Acoustics, at Lund Institute of Technology, during the period February 2009 to May 2009.

Firstly, I would like to express my deepest gratitude to my supervisor, Dr. Sc. Delphine Bard, for her patience and her great assistance during this time.

During this time I have also received a great amount of help and guidance from Pia Johansson and Kristian Stålne. I would also like to thank all the staff at the Structural Mechanics Division and the Engineering Acoustics Division.

Another special thanks goes to my friends which help me with the measurements  and to Usue who has always  been supporting me.

Thank you for this magnificent opportunity.

Lund, May 2009

# Abstract

Nowadays, wood floors are spread around the world in residential housing. Furthermore, in the future a higher dependency to this material will grow due to its low environmental impact. However this material has been used for several years as floor construction material, there are still some drawbacks when it comes to vibrations due to its low weight.

In this thesis, vibrations induced by human walking have been examined in an experimental floor. The objective of this project was to find the acceptability of the floor with regard to vibrations. Another objective was to carry out the tests in two different directions in order to determine how much the length of the span affects vibrations. The long term goal is to fabricate wooden floors of any size where residents are not disturbed by any vibration.

In this project a rectangular experimental floor made of particle board was used. The floor was simply supported in the four corners. This floor was tested with the help of twenty volunteers who were asked to complete several tests. The first test was a subjective test in which the volunteers were asked to mark the serviceability of the floor with regard to vibrations when they were walking on it. The results from this test show that the immense majority of the volunteers found the experimental floor structure unacceptable or absolutely unacceptable for the first walking line. In contrast, for the second walking line, half of the volunteers rated as acceptable. In the second test, the test subjects were sat on a chair as a person was walking over both walking lines. In this case, both lines were rated as unacceptable or absolutely unacceptable.

The other experiment consisted in measuring the accelerations of the floor induced by the test persons with the help of accelerometers. This data was processed by the computer code *Accelero* and the overall weighted accelerations were obtained. These were evaluated according to the former ISO 2631-2:1989 and a method proposed by the researchers Toratti and Talja. The results from these direct measurements were in agreement with the results obtained in the subjective tests. In other words, the averages of the overall weighted accelerations considered in this report exceed the limits considerably.

Using the direct measurements, the natural frequencies of the floor were obtained. These results were corroborated with some mathematical calculation. Nevertheless, some differences between can been seen due to the amount of simplification that were made. In order to improve the accuracy of these calculations, some finite element modeling must be done.

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# 1 Introduction

## 1.1 Background

Wood is one of the most traditional materials used in floor construction. This type of floors has been used for many years and this tendency will not decay in the near future. As climate change is a reality and new environmental restrictions are expected from the government in order to tackle this issue, wood will be very present in our future due to its low environmental impact. Nevertheless, this material, especially on floors, sometimes shows some undesirable behavior such as vibrations;as a result of its light-weight.

In modern construction, wooden floors are made of a considerable depth in order to avoid annoying vibrations induced by human walking, for example. Nonetheless, this increase on the depth of the floor does not guarantee an adequate performance in terms of vibrations as it has been shown by real examples such as in the residential wooden building in Limnologen (Växjö).

Nowadays, bigger rooms are preferable on houses or flats. Nevertheless, this new fashion trend aggravates the problem of vibrations. In other words, the bigger the space without supports in the room, the longer the span and the increase the deflection on the floor. This deflection is one of the main factors that cause annoying vibrations. A clear real example of this phenomenon has been experienced in the highest wood building in Sweden called Limnologen (Växjö).

## 1.2 Objective

The goal of this project is to measure the vibrations produced by human walking on a long span wooden floor. The main purpose, is to find out how the different characteristics of an individual affect on the performance of the floor. For instance, in this experiment the relationship between gender and overall weighted acceleration is on studied.

## 1.3 Method

In order to carry out this experiment, a wooden floor was assembled on the laboratory. Fifteen accelerometers were placed covering the most important areas of the floor. These were needed to obtain the accelerations induced by human walking. As the vibrations affect human in different ways, a subjective test was also carried out. As a result, 20 people, from which 10 were male and 10 female, were asked to filled up a questionnaire after assessing the intensity and acceptability of the vibrations produced on the floor by human walking.

# 2 Experimental Wooden Floor Details

The wooden floor structure is formed by 5 beams and 2 particle boards. The beams have a cross-section area of 22x4800 $mm^2$ and the distance between them was approximately 530 mm. These beams were made of hard wood. Above the beams was the flooring. This was assumed to be built up from four wood particle boards forming a total surface area of 4800x2400 $mm^2$. The thickness of these boards were 15 mm.

The structure explained above was simply supported in six locations which were at both ends of the central and the outer beams. The triangular supports were made of steel with a height of 30mm. Due to the high deflection of the floor, some metallic plates (15mm) were used in order to raised the structure.

Some additional information of the materials can be found on the table below:

*Table 2.1: Material characteristics.*

| | Wood | Particle Board | Steel |
|---|---|---|---|
| Density ($kg/m^3$) | 470 | 720 | 7800 |
| Young's Modulus(GPa) | 0,8 | 3 | 210 |

In the first picture, is shown the structure under study is shown and below, there is a picture showing in detail one of the supports.

*Figure 2.1: Experimental floor.*

*Figure 2.2: Supports.*

# 3 Basic Vibrations Theory

The vibrations subject to study in this project are forced vibrations. In other words, the vibration takes place under the excitation of external forces. In this case, the external forces are the steps caused by human walking.

The numerous graphs used in this project are plotted in two different domains which are, the time domain and the frequency domain. In order to plot the vibration signal in the time domain, time versus acceleration is used. On the other hand, frequency against amplitude is plotted to represent the frequency domain. Two examples are shown below:

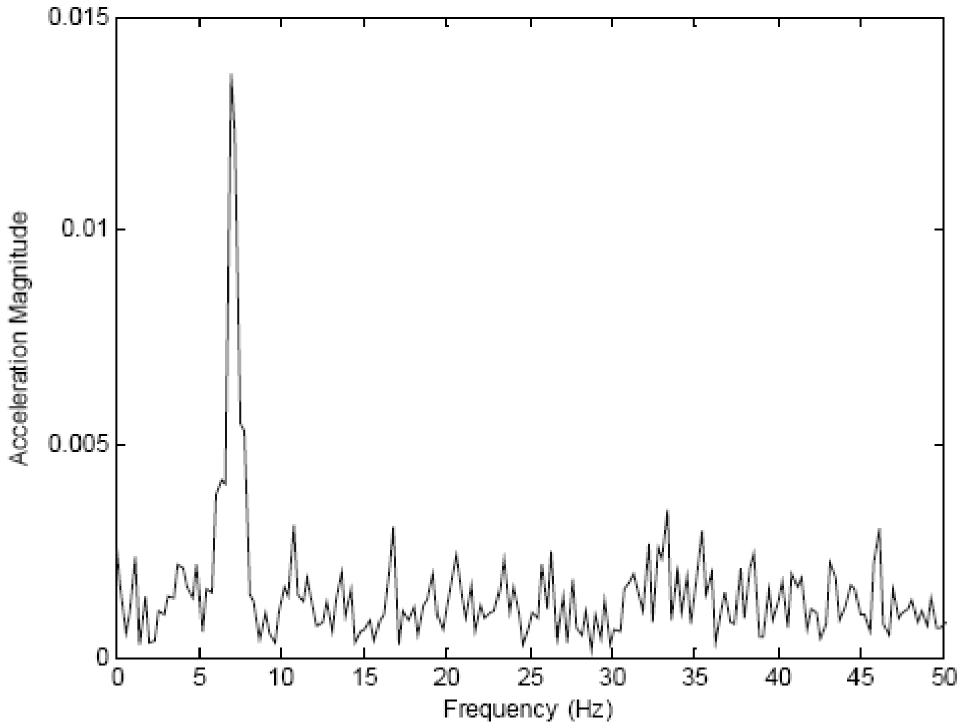



*Figure 3.1: The vibration signal presented in the frequency domain as amplitude plotted against frequency (Johansson 2009).*

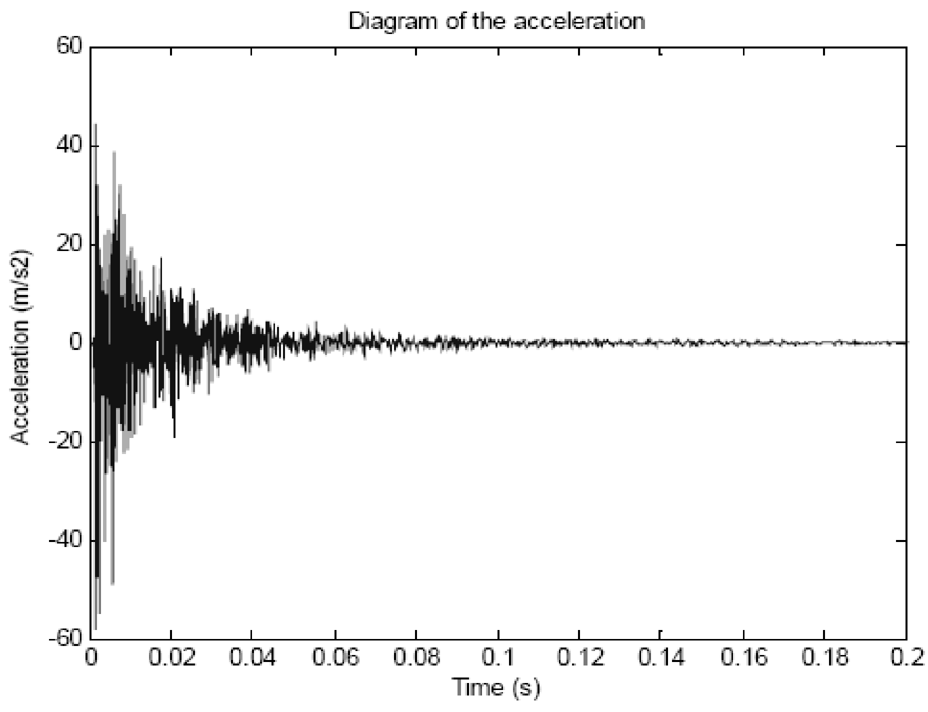



*Figure 3.2: The vibration presented in the time domain as accelerations plotted against time (Johansson 2009)*

## 3.1 Natural vibration frequencies

Natural frequencies are properties of the dynamic system which depend on its mass and its stiffness distribution. This frequency is at which the system vibrates naturally. These frequencies do not have a fixed number. In other words, its number is unlimited.

## 3.2 Resonance

When a dynamic force is applied onto an system, this will tend to oscillate. But if the system oscillates at its maximum amplitude, it means that resonance is occurring. If an idyllic example is mentioned where damping does not exist, the resonance frequency will be equal to the natural frequency. As it is shown below on the graph, when the damping is equal zero, the transmissibility is infinite. However, every structure has damping in order to prevent the oscillations.

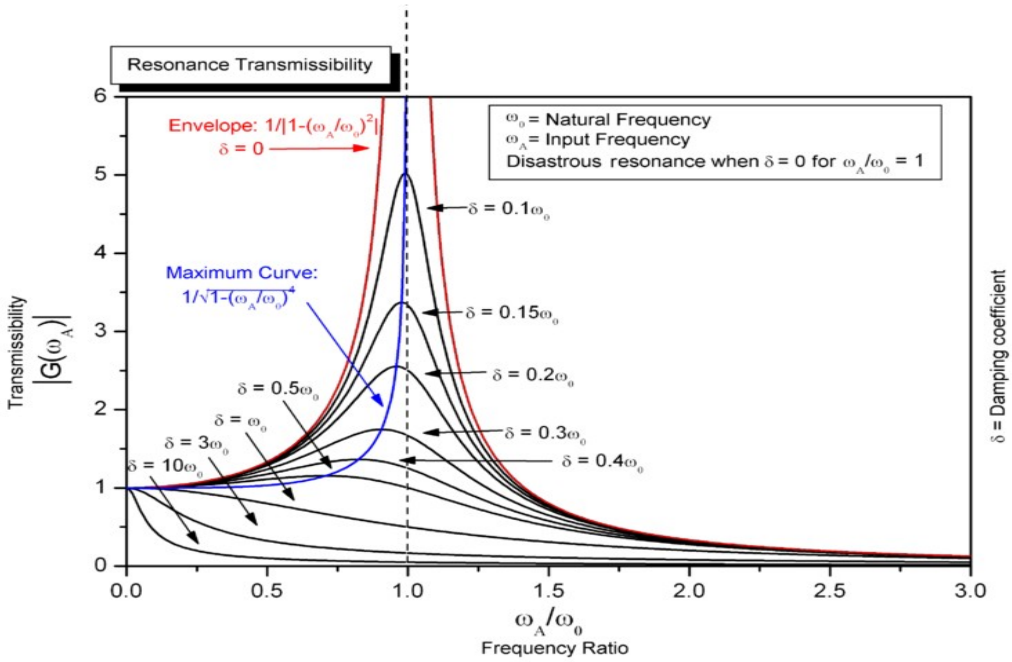



*Figure 3.3: Deformation response factor for a damped system excited by harmonic force (wikipedia).*

## 3.3 Terms

- **Springiness**

Springiness, which especially occurs in light-weight floor, is when the person causing vibrations acts as the source and receiver of the vibrations at the same time (Pavic & Reynolds 2002b)

- **Low-frequency floor**

A floor is considered high frequency when its fundamental frequency is above 10 Hz (Talja & Toratti 2006).

- **r.m.s acceleration**

r.m.s stands for root mean square and it is a way of measuring the intensity of the vibrations.

# 4 Human perception and response to the whole body vibrations

As it is well explained in the ISO 2631\ 1-1985, there are many complex factors determining the human response to vibrations. As a result, an immense research has been carried out. Nevertheless, due to the complexity mentioned before, no clear limit for acceptable magnitudes of vibration in buildings has been stated yet by the respective institutional bodies.

## 4.1 Whole-body vibrations

There are different sources of vibration affecting humans such as hand-held power tools, vehicles, vibrations in buildings,etc. These can be divided into whole-body vibrations or vibrations which influence only a part of a the body (Johansson 2009).

In this project, the vibrations induced to the participants are affecting their whole body. Due to the high subjectivity of the human perception and response to whole-body vibrations, limits for this matter are arduous to set.

## 4.2 Perception threshold

Some research has been carried out in order to set values for the perception threshold. This values can be considered as the limit for the acceptance of vibration. According to ISO 2631-1:1997, the occupants of residential buildings are likely to complain if the vibration magnitudes are only slightly above the perception threshold. Nevertheless, the perception is highly subjective and many factor can alter it, so its prediction is not an easy task. However, in the same ISO is mentioned that a fit person can just detect a $W_k$ weighted vibration with a peak of 0.015 $m/s^2$ when the individual is fifty percent alert.

Some research in this field that ought to be mentioned is the work of Reiher and Meister (1931). This study was one of the first in this area and they produce the Reiher-Meister scale. Another important research was carried out by Griffin in 1990.

## 4.3 Variables which affect the response

Several number of sensory systems are involved in the perception of vibrations. This systems are the visual system, the auditory system, the vestibular system and the somatic system. As a result, the determination of the acceptance limit is very complex.

Human response to whole-body vibration depends on the characters of the vibration, i.e. amplitude, frequency, duration, direction, and so on. The response is also influenced by the inter- and intra-subject differences, as for example age, gender, posture, fitness, type of activity, attitude, or motivation (Johansson 2009).

## 4.4 The effect of the whole-body vibrations on health

As it is stated in the ISO 2631-1:1997, a long-term high-intensity whole-body vibrations can result in a health risk in many internal parts of the human body, specially in the lumbar spine. These symptoms are not immediate and usually they can take several years to show.

# 5 Existing criteria and limit value

In this chapter, a perspective of the current situation is given. Also, it is shown the evolution in the standards throughout the years.

## 5.1 Eurocode

There is some design rules regarding the vibration serviceability of timber structures. Similar to the Swedish design regulations, a static and a dynamic criterion must be fulfilled in the case of high-frequency timber floors in residential buildings (EN 1992-1-1 & EN1995-1-1)(Johansson 2009).

## 5.2 ISO 2631-1:1997

This International Standard is focused on the vibration transmitted to the whole human body; as its title indicates (Vibration and shock – Evaluation of human exposure to whole-body vibration). In this ISO Standard, exposure vibration limits has not been included due to the highly subjective response of the human individuals when are subjected to whole-body vibration. Nevertheless, methods of vibration measurements are defined.

The weighted root-mean-square acceleration is considered as the main quantity of vibration magnitude. This value will help, when using the three annexes provided in this ISO, to establish the possible effects of vibration on health, comfort and perception and motion sickness.

Another information which must be recorded is the duration of the measurements. For instance, a human individual usually will be more annoyed when it is subjected to long periods of whole-body vibration.

## 5.3 ISO 2631-2:2003

The title of the second part of ISO standard 2631 is *Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration – Part 2 : Vibration in buildings (1 Hz to 80 Hz).* This standard is applicable to the evaluation of vibration in buildings with respect to comfort and annoyance of the occupants; it is not applicable when investigating the effects of vibration on human health and safety (Johansson 2009).

In this edition of the standard, limit values have been excluded, since research findings in the area of acceptable magnitudes of vibration are too widespread to be presented as guidance values in an international standard. Instead the standard recommends a method for a measurement and evaluation of whole-body vibrations in buildings in order to encourage a uniform collection of data, which will facilitate the establishment of limit values on the future (Johansson 2009).

For the evaluation of the measured accelerations the standard recommends using overall weighted values, see ISO 2631-1:1997. A frequency weighting curve $W_m$ is defined and recommended to be used irrespective of measurement direction or posture of an occupant. This frequency weighting curve is the same as the curve called $W_k$ in ISO 2631-1:1997. The standard also states that it is enough to consider and evaluate vibration in the direction with the highest frequency-weighted vibration magnitude (ISO 2631-2:2003). Since the experimental floor in this study is subjected to human walking, the main vibration direction will be the vertical direction, which means only the accelerations in this direction must be measured (Johansson 2009).

The standard emphasizes that human response to building vibration is in many cases not only a function of vibration magnitude, but also depends on secondary effects such as noise, expectations , and economic,social, or other environmental factors. Temporary disturbances such as construction work and transient events are given as examples of situations where significantly higher vibration magnitudes can be tolerated. If vibration last during a long period, the occupants might get familiarized and the adverse comment threshold might change. Another example is that adverse comment may arise due to secondary effects that are associated with vibration, such as the rattling of windows or ornaments or other visual effects that may emphasize the disturbance (Johansson 2009).

For this reason, guidelines for collecting data concerning human response to building vibration are given in an annex. These guidelines encourage users to not only measure vibration magnitudes but also collect data about all the other factors in a building that might affect human response to vibration. Parameters that should be reported are among others the character of the vibration, i.e. continuous, intermittent or impulsive vibration, the exposure time, measured noise level related to the vibration, and visual affects such as swinging of suspended features (ISO 2631-2:2003) (Johansson 2009).

## 5.4 ISO 2631-2:1989

As it is suggested in Pia Johansson report (2009): The version ISO standard 2631-2 has been cancelled and replaced by the newer edition ISO 2631-2:2003. However, the former edition is interesting because in this edition tentative vibration limits are given in the form of base curves.

There is one base curve for vibration in the foot-to-head direction. This base curve represents vibration magnitudes that cause approximately the same annoyance. When evaluating the vibration serviceability of a structure the base curve should be used together with multiplication factors.

These multiplication factors take into consideration the time of day and the use made of the occupied space, i.e. office, residential, etc. The multiplication factors are given in an annex, and they are result a result of a number of investigations of satisfactory magnitudes of building vibration with respect to human response, i.e. the multipliers are based on the state-of-the-art information present at that time.

For residential housing, there are a few different factors depending on the time by which the base curve must be multiplied. If the vibration is occurring during the day, the factor varies from 2 to 4. For this experiment a value of 4 has been used. On the other hand, for night time, a factor of 1,4 is suggested. In the graph below the base curve and the other two curves can be seen.

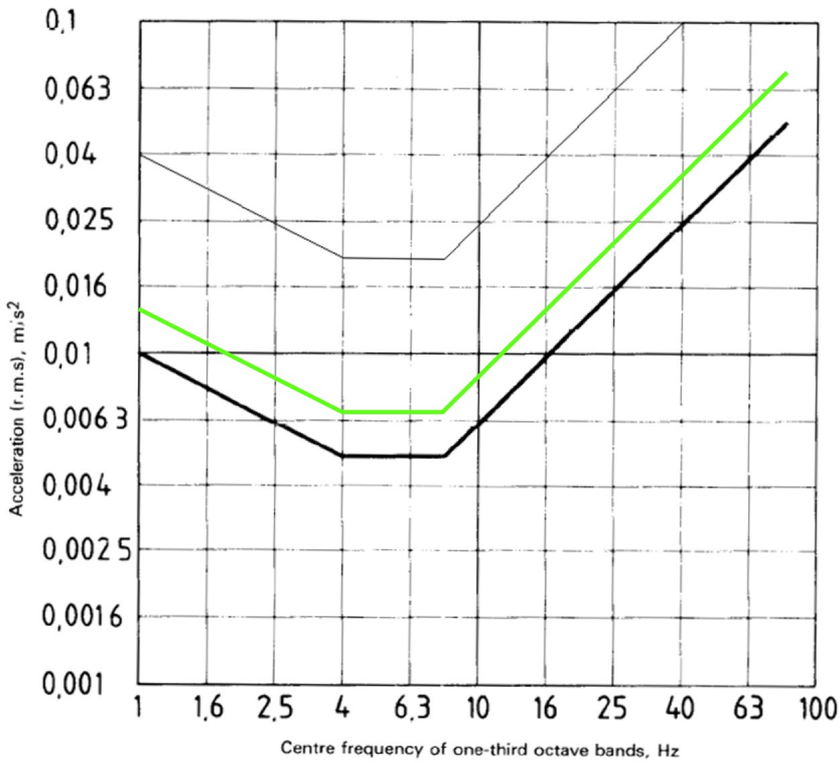



*Figure 5.1: Building vibration z-axis base curve for acceleration. The middle curve and the thin curve is valid for residential houses (ISO 2631-2:1989).*

## 5.5 Classification and acceptance limits of human induced floor vibrations according to Talja and Toratti

The main guidelines followed in this experiment are the ones established by the researches Tomi Toratti and Asko Talja. They have carried out an extensive research during the last decade in vibration serviceability of floors by human sense perception. As a result, they produced a set practical guidelines in order to asses the vibration serviceability of floors and suggest some criteria and limiting values (Toratti & Talja 2006).

Toratti and Talja believe that 10 Hz is the fundamental frequency value that divides the floors into low-frequency and high-frequency. In other words, when the fundamental frequency is above 10 Hz the floor will be considered high-frequency and vice versa. Also, they stated that local displacement due to 1 kN point load must be used in the design of high-frequency floors. On the other hand, acceleration is used for the design of low-frequency floors.

As it is shown below in the table 5.1, Talja and Toratti divided the vibration of floors into five different categories depending on its intensity. The indications given in this table are very subjective due to the sensibility of vibrations, which varies enormously from one individual to another. This class represents the sense perception of a sitting person and the sense perception from vibrations objects.

*Table 5.1: The vibration classification of floors based on the intensity of the vibration (Toratti & Talja 2004)*

| Body Perception | Vibration of Articles |
|---|---|
| A) The vibrations are usually imperceptible.<br>B) The vibrations are barely perceptible<br>C) The vibrations are perceptible.<br>D) The vibrations are clearly perceptible.<br>E) The vibrations are strongly perceptible. | 1. The clinking of a glassware and the leaf movements of a plant (in a pot) are usually imperceptible.<br>2. The clinking of a glassware usually imperceptible and the leaf movements are barely perceptible.<br>3. The clinking of glassware is barely perceptible and the leaf movements are perceptible.<br>4. The clinking of glassware and the leaf movements are clearly perceptible.<br>5. The clinking of the glassware and the leaf movements of a plant are strongly perceptible. |

The following table was also proposed by the two researches and it gives a proposal for the lowest permissible vibration class.

*Table 5.2: Proposal for the vibrations classes in office and residential buildings (Toratti & Talja 2004).*

| | |
|---|---|
| **A1** | Normal class for vibrations transferred from another apartment.<br>Special class for vibrations inside one apartment. |
| **B2** | Lower class for vibrations transferred from another apartment.<br>Higher class for vibrations inside one apartment. |
| **C3** | Normal class for vibrations inside one apartment. |
| **D4** | Lower class for vibrations inside one apartment. For example attics and holiday cottages. |
| **E5** | Class without restrictions. |

### 5.5.1 Subjective test

As it has been mentioned previously, the subjective test method carried out in this experiment has been inspired in Toratti and Talja method. As the human body is a very sensitive vibration meter

(Toratti and Talja 2006), subjective test are vital in order to delimit the vibration performance of the floor under observation.

During the test, a walker (80kg preferable) would walk back and forth. In every walk the walker should step on the reference point which usually is the point where the largest deformation will occur.

On the other hand, the observer will remain seated on an uncovered foot stool at the observation point. This will be located where the highest vibration is expected to take place. In the simplest of the cases such as in a rectangular floor, Talja & Toratti suggest that the distance must be not less than 600 mm. However, for more complex floor structures such as multi-span floors and raised floors, this distance can vary (Talja & Toratti 2004). A set up test example it is shown in the figure below.

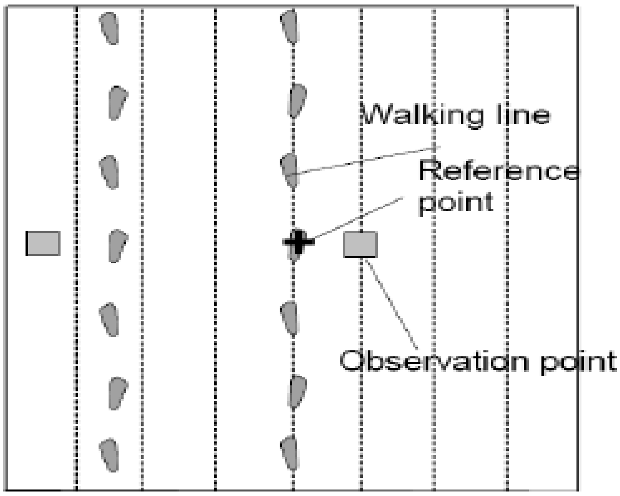



*Figure 5.2: Examples of walking lines corresponding observation points (Toratti & Talja 2004).*

In the case of a high-frequency floor, the walker should walk at a speed of 1.5 m/s which correspond to a frequency of 2 Hz.

The observer, placed in the observation point, is asked to assess the intensity and serviceability of the vibrations of the floor due to the walker's walking which must cover three times the walking line distance.

When the observer is asked to classify the intensity of the vibrations, the following rates options are available:

- Imperceptible
- Barely perceptible
- Clearly perceptible
- Strongly perceptible

Finally, when an assessment of the acceptability of the vibration in a newly built living room floor is required, the observer options are the followings:

- Absolutely acceptable
- Acceptable
- Unacceptable
- Absolutely unacceptable

Another procedure that Talja and Toratti suggest is to let the observers walk on the floor to experience the vibration and evaluate the respective results. An example of a form used for the classification of floor vibrations is shown in the table below.

***INTENSITY OF VIBRATIONS***
The vibrations are
- imperceptible **(No)**
- barely perceptible **(B)**
- clearly perceptible **(C)**
- strongly perceptible **(S)**

***ACCEPTABILITY OF VIBRATIONS***

Is the floor acceptable in a newly built living room ?
**+** yes **++** absolutely acceptable
**-** no **- -** absolutely unacceptable

| Test 1 | Intensity | | | | Acceptability | | | |
|---|---|---|---|---|---|---|---|---|
| | No | B | C | S | ++ | + | - | - - |
| Body perception | | | | | | | | |
| Clinking of a coffee cup | | | | | | | | |
| Leaf movements of a pot plant | | | | | | | | |
| Water rippling in a glass bowl | | | | | | | | |
| Chinking of a glass pane | | | | | | | | |

*Figure 5.3: Assessment form for rating the vibrations (Toratti & Talja 2004).*

### 5.5.2 Measurements

The acceleration is obtained using an accelerometer which will be placed on the observation point. It is important to keep the same walker in all the experiments in order to maintain the same vibration source.

The acceptance limit used is the weighted r.m.s. acceleration of all frequency bands:

$$a_w = \sqrt{\sum_i (W_{k,i} a_i)^2} \qquad \text{(Talja \& Toratti 2004)}$$

### 5.5.3 Acceptance limits

The table below shows the limiting values for all the vibration classes. In order to develop this table, Toratti and Talja have gathered information from subjective test and direct measurements during a decade(Talja & Toratti 2006).

| | Dynamic vibration values | | | | Static deflection values | |
|---|---|---|---|---|---|---|
| | $f_0 < 10$ Hz | | $f_0 > 10$ Hz | | $f_0 > 10$ Hz | Floor plate or superstructure |
| | $a_{w.rms}$ [m/s$^2$] | $v_{max}$ [mm/s] | $v_{rms}$ [mm/s] | $\|u_{max}\|$ [mm] | Global deflection [a] $\delta_0$[mm/kN] | Local deflection [b] $\delta_1$[mm/kN] |
| A | ≤ 0.03 | ≤ 4 | ≤ 0.3 | ≤ 0.05 | ≤ 0.12 | ≤ 0.12 |
| B | ≤ 0.05 | ≤ 6 | ≤ 0.6 | ≤ 0.1 | ≤ 0.25 | ≤ 0.25 |
| C | ≤ 0.075 | ≤ 8 | ≤ 1.0 | ≤ 0.2 | ≤ 0.5 | ≤ 0.5 |
| D | ≤ 0.12 | ≤ 10 | ≤ 1.5 | ≤ 0.4 | ≤ 1.0 | ≤ 1.0 |
| E | > 0.12 | > 10 | > 1.5 | > 0.4 | > 1.0 | > 1.0 |

[a] Deflection of main beams

[b] Deformation caused by floor tops (measured at a distance of 600 mm, Figure 1) which are deformations of top plate, floating floor or raised floor.

*Figure 5.4: Tentative acceptance limits for vibration classes (Toratti & Talja 2006).*

# 6 Subjective Test

The purpose of carrying the subjective tests is to evaluate the vibration serviceability of the floor. The questionnaire used on this experiment,see appendix X, was taken by a previous research made by Pia Johansson (2009). Some modifications were made in this questionnaire for this project due to the difference of the experimental structure.

The chosen method in this project has been thought to be as similar as possible to the one proposed by Talja and Toratti. This will help to compare the results obtained in this project with results from future projects. The subjective test was divided into two different parts. Firstly, the volunteers walk over the set walking line. Then, they were asked to rate the intensity of the vibrations and the acceptability of the floor if it would have been installed in a newly built office. In order to rate this, the questionnaire provided two multiple choice questions. Finally, the test participants were asked to rate the vibration performance of the floor structure on a scale from 1 to 10, where 1 means "very poor" and 10 means "very good" (Johansson 2009).

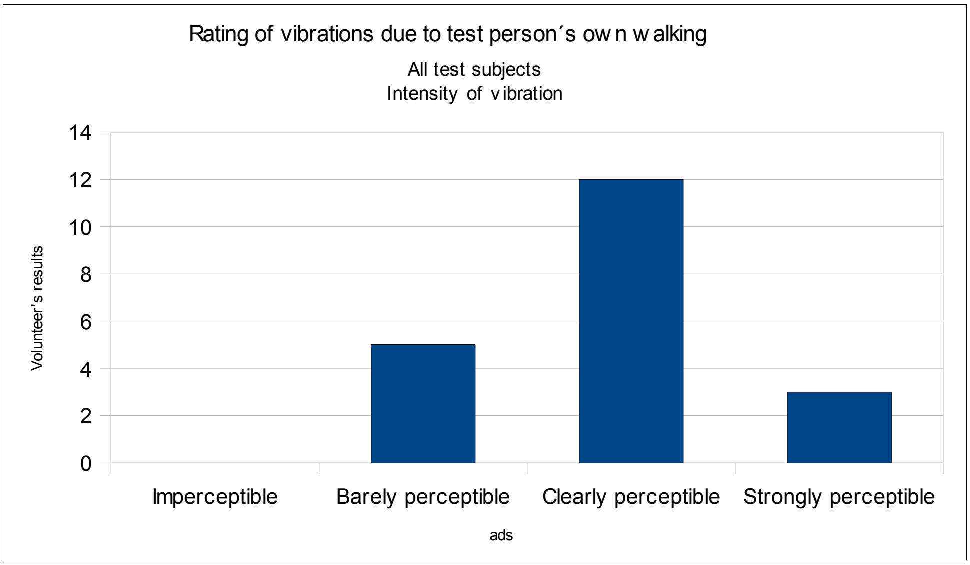
In the second part of the test, the participants were placed on an uncovered foot stool which was located at the observation points. The distance from this point to the reference point varies for the two different walking lines. For the first walking line, this distance was 600 mm which is the suggested value by Talja and Toratti. Nevertheless, for the second walking line the distance was 700 mm due to dimension issues. The walker weighting 75 kg passed three times with a step frequency of 2 Hz. Then the volunteer was asked to answer the same set of questions explained in the paragraph above.

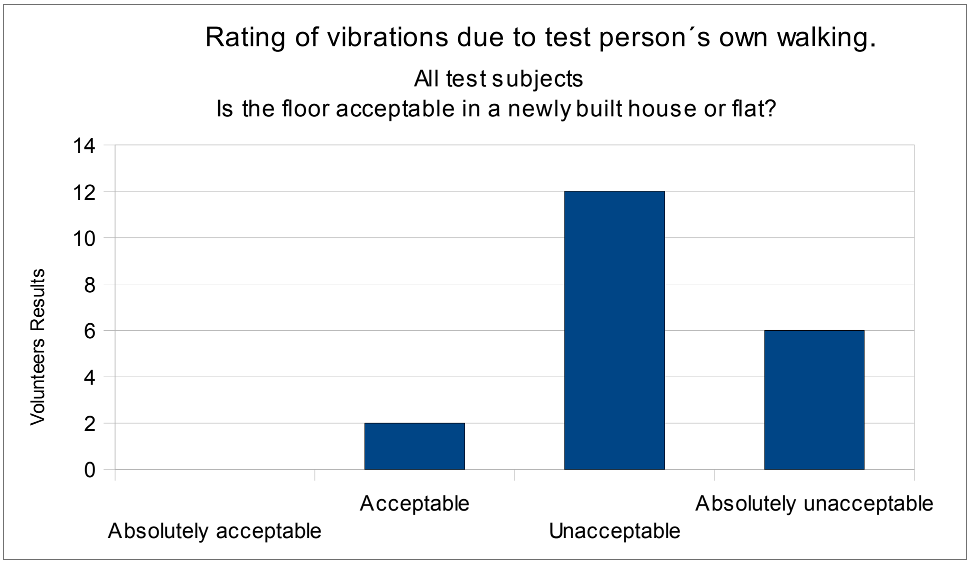
## 6.1 Subjective test results

The results are split into two due to two different walking lines set for the experiment. 20 volunteers took part on it with the same amount of males than females. All the data obtained in this experiment can be found in the appendix 2.

### 6.1.1 Test results: Walking line 1

As it is shown on the table below, the intensity of the vibration was found clearly perceptible by the majority (60%) . As a result, when the participants were asked about the acceptability of the floor, 60% found it unacceptable and 30% absolutely unacceptable.



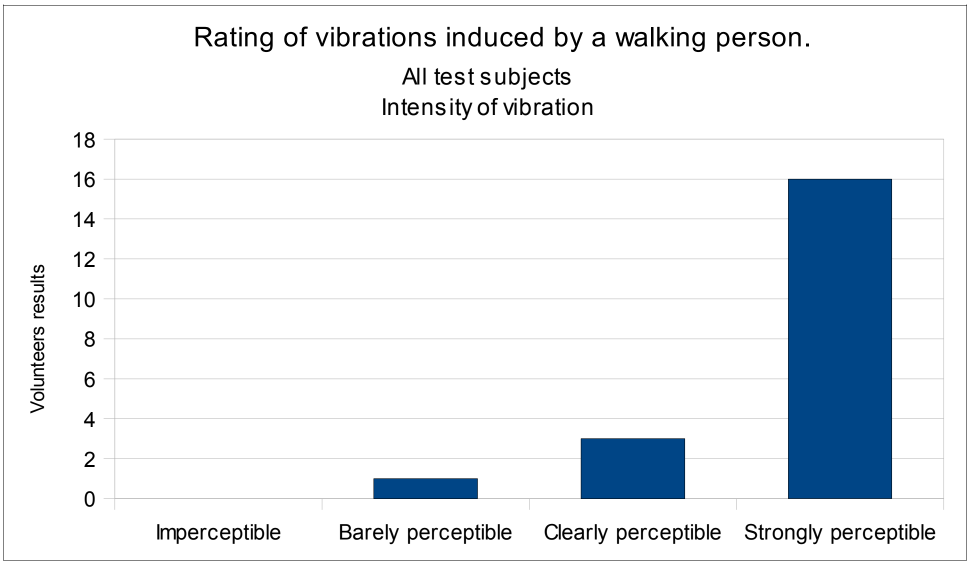

Finally, in the table below the answers of the participants are shown when they were asked about vibration serviceability of the floor.

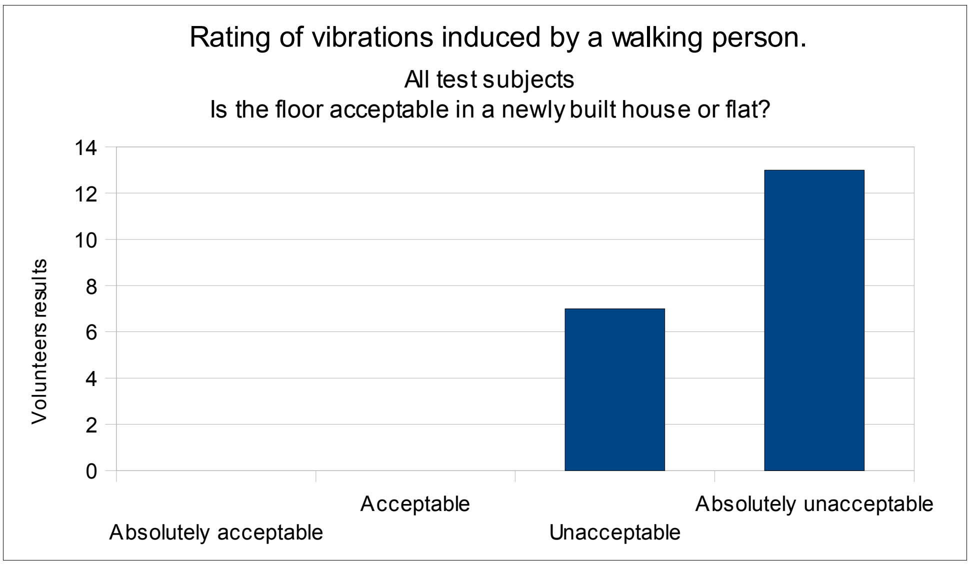
| Walking Line 1 | Age (years) | Weight (kg) | Q1.3 |
|---|---|---|---|
| Mean value | 23.95 | 65.5 | 3.9 |
| Standard Deviation | 3 | 12.01 | 1.34 |

*Figure 6.1: Rating vibration performance of the floor.*

*Q1.3: Vibrations due to test person's own walking.1=very poor, 10=very good.*

The next set of data comes from the second part of the experiment when the volunteers were placed on a chair at the same time a person walked over the walking line three times. In contrast to the previous case, 80% of the participants found the vibrations strongly perceptible and no one found the floor acceptable for a newly built house or flat with a 65% finding it absolutely unacceptable.



Again,  on the table below the performance results are found.

| Walking Line 1 | Age (years) | Weight (kg) | Q2.3 |
|---|---|---|---|
| Mean value | 23.95 | 65.5 | 2.55 |
| Standard Deviation | 3 | 12.01 | 1.02 |

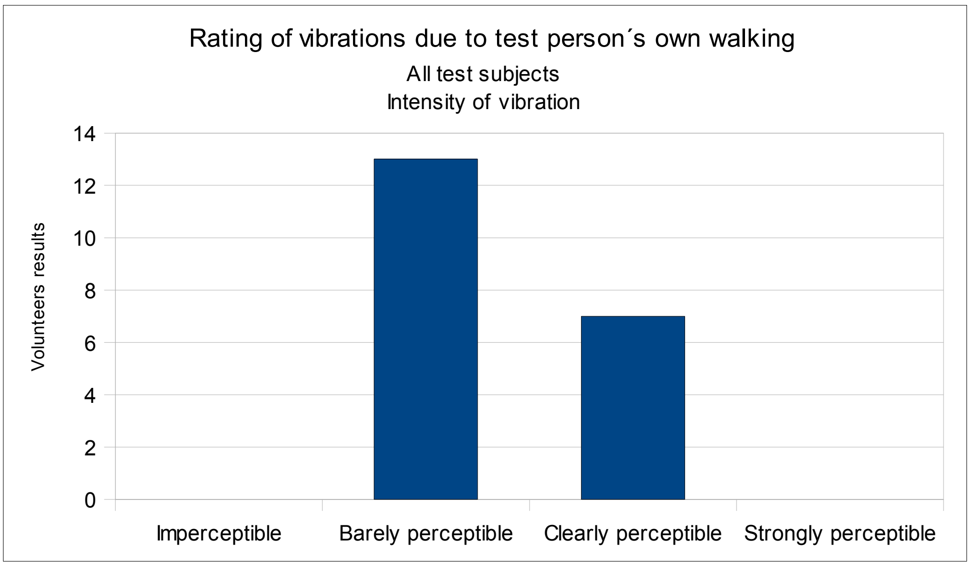
*Figure 6.2: Rating of the vibration performance of the floor.*

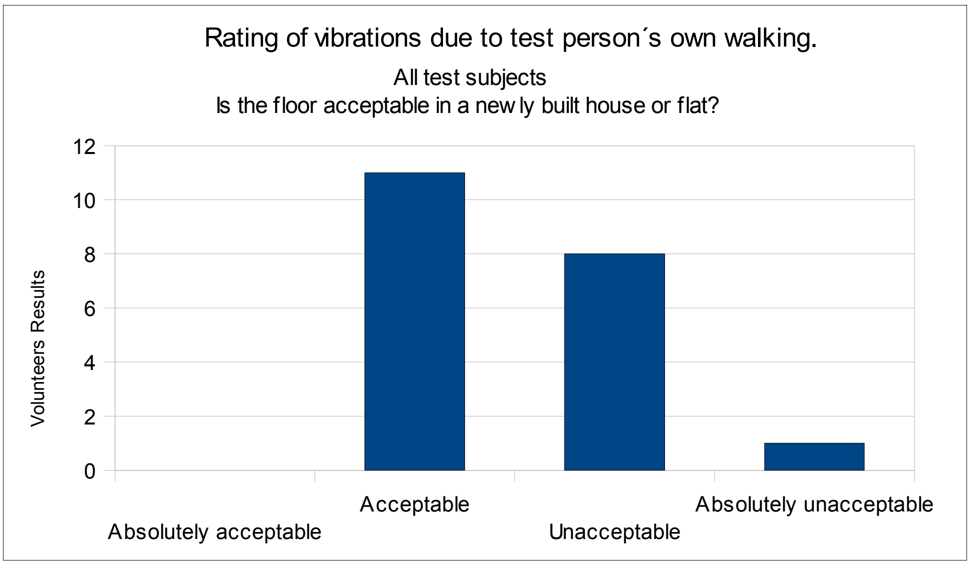
*Q2.3: Vibrations due to another person walking by. 1=very poor, 10=very good.*

It is clearly shown from the results, that in the second case when the participant is sitting on the chair the vibrations are more perceptible. These findings are in agreement with the results obtained by Johansson (2009). One of the explanation given by Johansson about this difference is the following: “During the process of normal walking the human body is subjected to accelerations. Therefore, the nervous system and the brain are used to these types of accelerations and are capable of disregarding them”(Johansson 2009).

### 6.1.2 Test results: Walking line 2

The following section presents the same data as above but when the experiment was carried out in the second walking line. Nevertheless, significant differences can be observed from the first walking line. For instance, when the participants were asked to rate the vibration after they walked, 65% answered that the vibrations were barely perceptible. Also, when it comes to the acceptability of the floor, an unexpected 55% of the participants rate the floor as acceptable. If this result is compared with the one in the previous section, using the second walking line the floor perform much better. The reasons for this phenomena could be that there is a smaller span between supports in the second walking line and that the floor is supported in the middle in that direction.



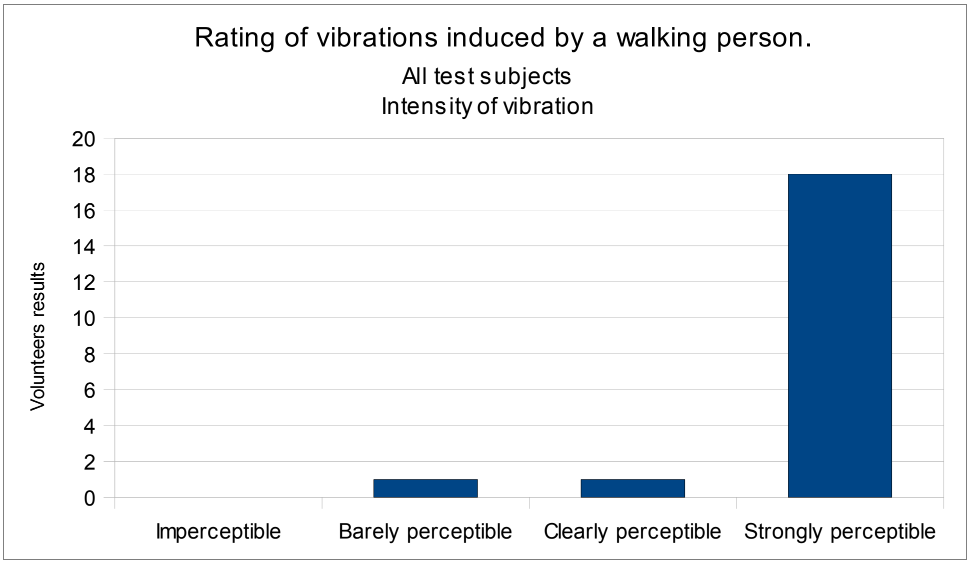


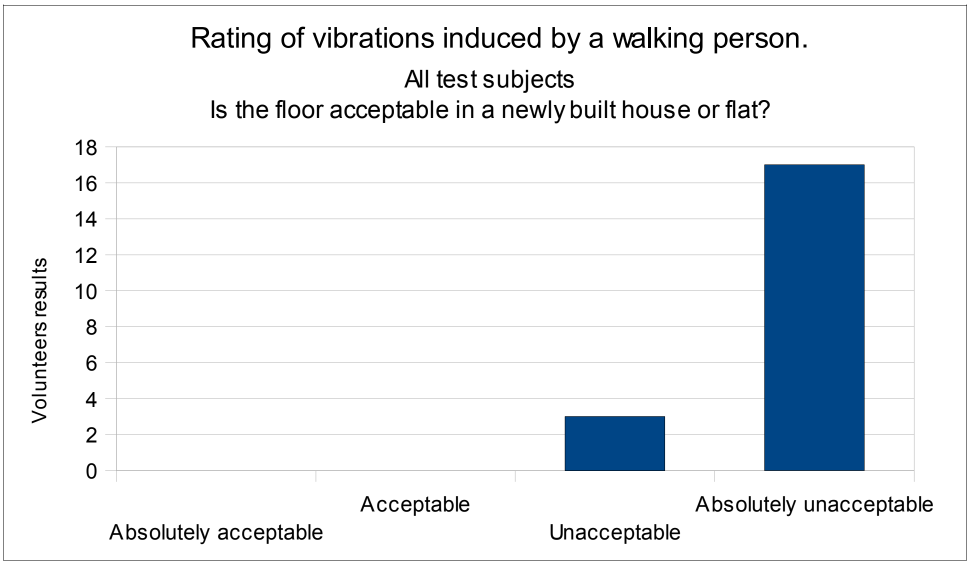

| Walking Line 2 | Age (years) | Weight (kg) | Q1.3 |
|---|---|---|---|
| Mean value | 23.95 | 65.5 | 5.25 |
| Standard Deviation | 3 | 12.01 | 1.67 |

*Figure 6.3: Rating of the vibration performance of the floor.*

*Q1.3: Vibrations due to test person's own walking.1=very poor, 10=very good.*

Nevertheless, when it comes to vibrations induced by a walking person, the results are more negatively extreme than for the first walking line. For instance, 90% of those asked believed that the intensity of the vibrations were strongly perceptible and 85% rated the floor as absolutely unacceptable.





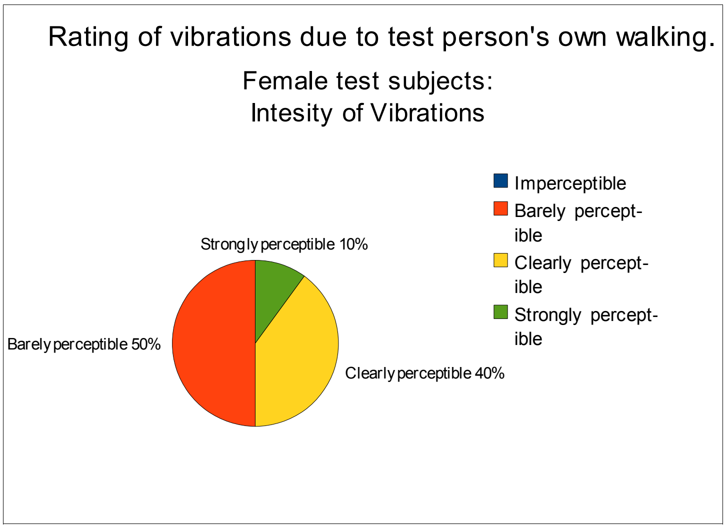

| Walking Line 2 | Age (years) | Weight (kg) | Q2.3 |
|---|---|---|---|
| Mean value | 23.95 | 65.5 | 1.85 |
| Standard Deviation | 3 | 12.01 | 0.85 |

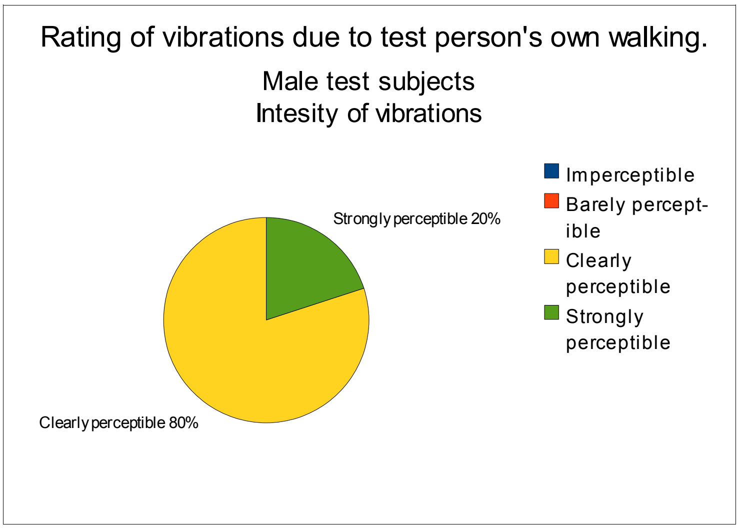
*Figure 6.4: Rating of the vibration performance of the floor.*

*Q2.3: Vibrations due to another person walking by. 1=very poor, 10=very good.*

### 6.1.3 Results depending on gender

In general, there has not been big differences between men and women in the subjective test. In this section, the intensity of the vibrations in the first walking line is discussed. This line has been chosen because it is where more differences can be found between female and female. The two pie charts below show how women were less sensitive than men. 50% of the female found the vibration due to their own walking barely perceptible in contrast with 0% of the male participants.






One of the reason for this difference between gender perception can be the weight. In general men are heavier than women and they generate higher frequencies when walking. Furthermore, heavy people are more sensitive to higher frequencies.

The rest of this data can be found in the appendix 2.

### 6.1.4 Discussion

The majority of the participants found the floor unacceptable or absolutely unacceptable in terms of intensity of vibrations. Also, the participants found the intensity of the vibrations more annoying when those were induced by another person.

The differences between the two walking lines were quite clear. With regard to vibrations induced by another person walking on the second walking line, the experimental floor was rated as absolutely unacceptable by the immense majority of the volunteers. Nevertheless, this walking line outperform the first walking line when the participants walk over the structure.

With regard to differences between gender, females were less annoyed by the vibrations then men.

# 7 Direct Measurements

## 7.1 Equipment

The equipment used in order to get the direct measurements were 15 accelerometer and one tapping machine. These devices are explained in the next following sections.

### 7.1.1 Accelerometers

An accelerometer is an electromechanical device that measures acceleration forces in three directions. However, in this experiment only vertical displacement was needed and the accelerometers used were the ADXL 202 with a bandwidth of 0-5 Hz.

In order to read the information obtained by the accelerometer, a computer program called *Accelero* (Delphine Bard) was used. This computer program converts the electrical signal into acceleration values.

Below can be seen in detail a picture of one of the 15 accelerometers available.


*Figure 7.1: Accelerometer ADXL 202.*

As it is shown on the picture, the accelerometers were screwed directly on to the floor where they measured the accelerations which were exposed to.

### 7.1.2 Tapping Machine

A tapping machine is an impact sound generator used to standardized impact sound measurements. It consist of five hammers each weighting 0.5 kg that drop from a standard height of 40 mm twice per second, giving an operating frequency of 10 Hz (Holterman & Petersson 2008). Nevertheless, for this experiment only one hammer of the tapping machine was used, giving a frequency of 2 Hz.

The picture below shows a the tapping machine used for this experiment.


*Figure 7.2: Tapping Machine.*

## 7.2 Measurements process

### 7.2.1 Experimental procedure

The test person was asked to walked in two different directions for this experiment. The first walked was in the lengthwise of the floor and it was named as the first walking line. The volunteers needed about 6 seconds to complete the first walked and seven accelerometers were needed to cover this length. The second walking line was placed across the floor, making it much shorter due to the dimensions of the experimental floor. As a result, only 4 seconds were needed by the test persons to complete the walked and just five accelerometers were used for this walking line.

In order to obtained accurate vibration measurements, the footprints used by the test persons were drawn on the floor. In every footprint a accelerometer was placed and the test persons were asked to step beside it.

### 7.2.2 Experiment set up

As it is mentioned above, 15 accelerometers were available at the time of the experiment. In the sketch below, the location of the accelerometers can be appreciated. The accelerometers with their numbers inside a circle form the first walking line. The arrows indicated the direction in which the volunteers were asked to walk. The second walking line is composed by the accelerometers with their number inside an square and the rest were placed in different locations in order to understand the vibration at these points.

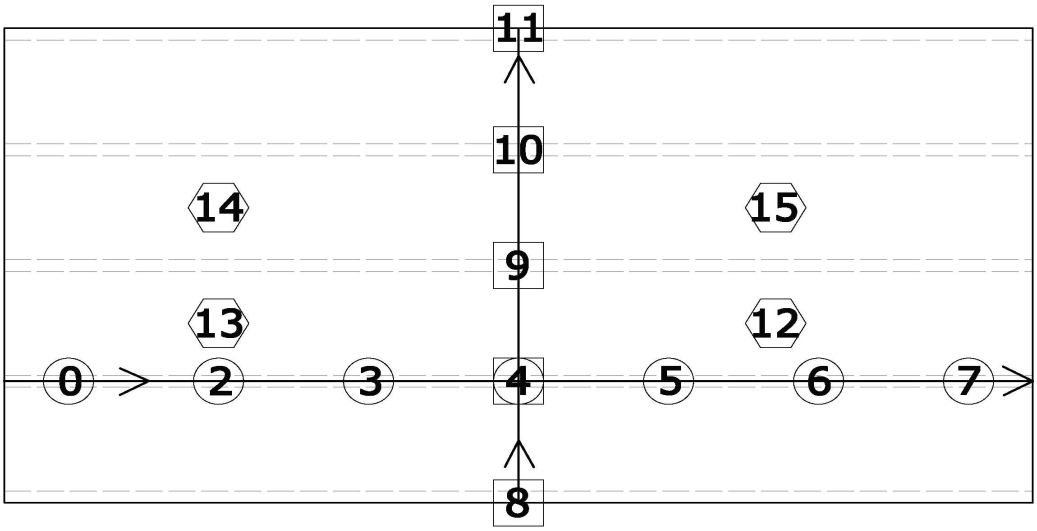



*Illustration 7.1: Location of the accelerometers on the experimental floor.*

*Numbers inside a circle form the first walking line. Numbers inside a square form the second walking line. And finally, the numbers inside the hexagon are free accelerometers.*

## 7.3 Overall weighted acceleration

In order to evaluate the vibration serviceability of the floor structure, the overall weighted acceleration is determined as Toratti and Talja propose in his method. This value is also recommended in the ISO 2631-1:1997 and in the ISO 2631-2:1989.

## 7.4 Results

All the results obtained from the measurements are presented in the next sections.

### 7.4.1 Walking line 1

In the tables of this section, the maximum, minimum and average acceleration across the floor can be seen. Also it is shown the averaging time used for calculation of the r.m.s. acceleration. As in the method proposed by Toratti and Talja, an averaging time of one second has been used. As a result, *Accelero* isolated the second with the individual largest impact.

*Table 7.1: Female overall weighted values of acceleration (m/s²).*

| | Averaging Time (s) | Min (across the floor) | No. Acc | Max (across the floor) | No. acc | Average (across the floor) |
|---|---|---|---|---|---|---|
| Alexia_WL1_1 | 1 | 0,095 | 11 | 1,363 | 7 | 0,520 |
| Alexia_WL1_2 | 1 | 0,078 | 11 | 1,231 | 7 | 0,444 |
| Cecile_WL1_1 | 1 | 0,114 | 8 | 0,571 | 5 | 0,311 |
| Cecile_WL1_2 | 1 | 0,079 | 11 | 1,093 | 7 | 0,487 |
| Curasan_WL1_1 | 1 | 0,074 | 11 | 0,640 | 0 | 0,375 |
| Curasan_WL1_2 | 1 | 0,161 | 11 | 0,842 | 0 | 0,468 |
| Delphine_WL1_1 | 1 | 0,100 | 11 | 0,690 | 0 | 0,285 |
| Delphine_WL1_2 | 1 | 0,149 | 11 | 0,807 | 7 | 0,388 |
| Flora_WL1_1 | 1 | 0,023 | 8 | 0,406 | 3 | 0,175 |
| Flora_WL1_2 | 1 | 0,111 | 11 | 0,767 | 0 | 0,337 |
| Hanna_WL1_1 | 1 | 0,228 | 8 | 0,860 | 0 | 0,516 |
| Hanna_WL1_2 | 1 | 0,184 | 11 | 0,921 | 7 | 0,536 |
| Mathilde_WL1_1 | 1 | 0,076 | 9 | 0,731 | 7 | 0,310 |
| Mathilde_WL1_2 | 1 | 0,107 | 11 | 1,071 | 7 | 0,419 |
| Pia_WL1_1 | 1 | 0,162 | 9 | 0,629 | 7 | 0,383 |
| Pia_WL1_2 | 1 | 0,154 | 11 | 0,787 | 7 | 0,446 |
| Sanna_WL1_1 | 1 | 0,121 | 11 | 0,762 | 7 | 0,239 |
| Sanna_WL1_2 | 1 | 0,098 | 9 | 0,753 | 7 | 0,323 |
| Yasmeen_WL1_1 | 1 | 0,096 | 11 | 2,687 | 7 | 0,200 |
| Yasmeen_WL1_2 | 1 | 0,127 | 9 | 1,087 | 7 | 0,435 |
| | | | | Average value Across the floor | | 0,380 |

*Table 7.2: Male overall weighted values of acceleration (m/s²).*

| | Averaging Time (s) | Min (across the floor) | No. Acc | Max (across the floor) | No. acc | Average (across the floor) |
|---|---|---|---|---|---|---|
| Andy_WL1_1 | 1 | 0,185 | 11 | 0,758 | 6 | 0,448 |
| Andy_WL1_2 | 1 | 0,024 | 8 | 0,947 | 6 | 0,339 |
| Georg_WL1_1 | 1 | 0,151 | 11 | 1,765 | 7 | 0,689 |
| Georg_WL1_2 | 1 | 0,115 | 11 | 1,877 | 2 | 0,545 |
| Ivan_WL1_1 | 1 | 0,171 | 11 | 0,661 | 7 | 0,380 |
| Ivan_WL1_2 | 1 | 0,211 | 8 | 0,964 | 7 | 0,498 |
| Jacin_WL1_1 | 1 | 0,055 | 11 | 0,657 | 6 | 0,336 |
| Jacin_WL1_2 | 1 | 0,177 | 11 | 1,289 | 7 | 0,543 |
| Matt_WL1_1 | 1 | 0,128 | 11 | 0,713 | 6 | 0,429 |
| Matt_WL1_2 | 1 | 0,070 | 9 | 1,213 | 7 | 0,447 |
| Matthias_WL1_1 | 1 | 0,104 | 9 | 0,951 | 7 | 0,543 |
| Matthias_WL1_2 | 1 | 0,187 | 8 | 1,373 | 0 | 0,632 |
| Michael_WL1_1 | 1 | 0,180 | 11 | 1,641 | 0 | 0,708 |
| Michael_WL1_2 | 1 | 0,114 | 11 | 0,687 | 3 | 0,444 |
| Miguel_WL1_1 | 1 | 0,106 | 11 | 0,575 | 0 | 0,293 |
| Miguel_WL1_2 | 1 | 0,076 | 11 | 0,675 | 2 | 0,353 |
| Pau_WL1_1 | 1 | 0,132 | 11 | 0,593 | 0 | 0,370 |
| Pau_WL1_2 | 1 | 0,117 | 11 | 1,374 | 7 | 0,611 |
| Yann_WL1_1 | 1 | 0,162 | 11 | 1,102 | 2 | 0,511 |
| Yann_WL1_2 | 1 | 0,068 | 9 | 0,890 | 13 | 0,428 |
| | | | | Average value Across the floor | | 0,477 |

The results obtained in this experiment were classified in the classification proposed by Talja and Toratti, see figure 5.4. Also, these values were compare with the limits recommended in the ISO 2631-2:1989, see table 5.1. The two limits proposed for residential area in this ISO are 0.02 $m/s^2$ for day time and 0,0069 $m/s^2$ for night time.

The total average value of the overall weighted acceleration across the floor is 0,429 $m/s^2$. The female value is 0,380 $m/s^2$ and 0,477 $m/s^2$ is the male one.

- Toratti and Talja

  $a_{w,rms}$ = 0,429 $m/s^2$ → Vibration class E.

  $a_{w,rms}$ = 0,380 $m/s^2$ → Vibration class E.

  $a_{w,rms}$ = 0,477 $m/s^2$ → Vibration class E.

  This vibration is considered as without restrictions. This results are in the same line as the subjective test results.

- ISO 2631-2:1989, t = 1s

  Using the same $a_{w,rms}$ as above, and comparing them with the day limit value ( 0.02 $m/s^2$ ), it can clearly be said that the results are much higher than the limits. As a result, the probability of adverse comments is really high. This is in agreement with the subjective tests results.

In the figure below an example of the acceleration against the frequency is presented. The three curves represent the base line (bottom curve), the limit for the night time (middle curve) and the limit for day time (top curve).

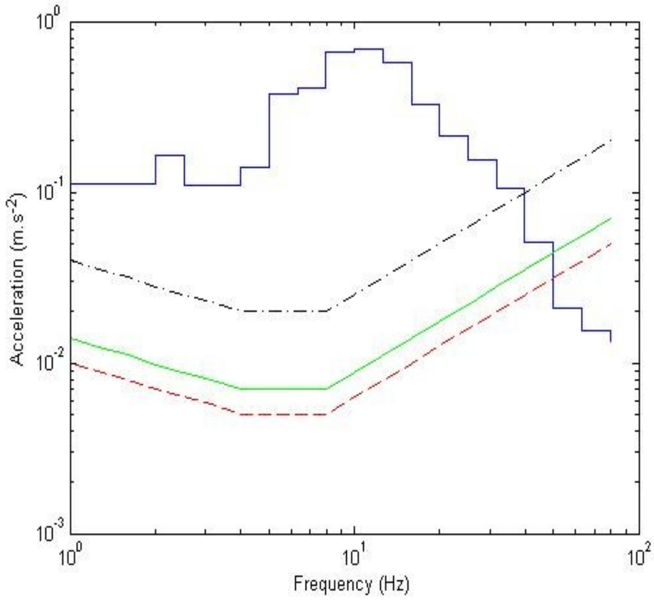



*Figure 7.3: Acceleration magnitudes in 1/3 octave bands with an averaging time of 1 second. The bottom line is the base curve of ISO 2631-2:1989. The line in the middle is the curve valid for residential for night time and the top one is the limit for day time.*

Another point to mentioned is the locations of the highest and smallest accelerations. The accelerometer which more times gave the maximum acceleration is number 7. The reason for this could be that the volunteers stepped outside the floor after stepping beside this accelerometer. On the other hand, accelerometer number 11 gave the minimum acceleration value the most times.

### 7.4.2 Walking line 2

For the second walking line, the same conditions as above are applied. However, the overall weighted acceleration are much lower than in for the first walking line. This can be compared with the subjected test result in which the test persons believed that the floor behaves in this direction slightly better than in the direction of the first walking line. All this can be appreciated in the tables 7.3 for females and 7.4 for males.

*Table 7.3: Female overall weighted values of acceleration (m/s²).*

| | Averaging Time (s) | Min (across the floor) | No. Acc | Max (across the floor) | No. acc | Average (across the floor) |
|---|---|---|---|---|---|---|
| Alexia_WL2_1 | 1 | 0,192 | 14 | 0,591 | 3 | 0,293 |
| Alexia_WL2_2 | 1 | 0,206 | 13 | 0,464 | 3 | 0,298 |
| Cecile_WL2_1 | 1 | 0,100 | 9 | 0,249 | 12 | 0,191 |
| Cecile_WL2_2 | 1 | 0,176 | 9 | 0,417 | 3 | 0,296 |
| Curasan_WL2_1 | 1 | 0,197 | 9 | 0,453 | 4 | 0,339 |
| Curasan_WL2_2 | 1 | 0,192 | 8 | 0,377 | 2 | 0,305 |
| Delphine_WL2_1 | 1 | 0,115 | 8 | 0,386 | 4 | 0,239 |
| Delphine_WL2_2 | 1 | ---- | --- | ----- | --- | ---- |
| flora_WL2_1 | 1 | 0,063 | 9 | 0,258 | 3 | 0,136 |
| flora_WL2_2 | 1 | 0,111 | 14 | 0,396 | 11 | 0,208 |
| Hanna_WL2_1 | 1 | 0,194 | 5 | 0,427 | 0 | 0,241 |
| Hanna_WL2_2 | 1 | 0,212 | 8 | 0,378 | 3 | 0,290 |
| mathilde_WL2_1 | 1 | 0,052 | 11 | 0,327 | 5 | 0,154 |
| mathilde_WL2_2 | 1 | 0,171 | 8 | 0,422 | 0 | 0,304 |
| Pia_WL2_1 | 1 | 0,173 | 8 | 0,334 | 10 | 0,266 |
| Pia_WL2_2 | 1 | 0,162 | 8 | 0,460 | 3 | 0,309 |
| Sanna_WL2_1 | 1 | 0,067 | 8 | 0,240 | 10 | 0,144 |
| Sanna_WL2_2 | 1 | 0,103 | 8 | 0,291 | 11 | 0,208 |
| Yasmeen_WL2_1 | 1 | 0,098 | 8 | 0,366 | 0 | 0,179 |
| Yasmeen_WL2_2 | 1 | 0,125 | 8 | 0,291 | 4 | 0,219 |
| | | | | Average value Across the floor | | 0,231 |

*Table 7.4: Male overall weighted values of acceleration ($m/s^2$).*

| | Averaging Time (s) | Min (across the floor) | No. Acc | Max (across the floor) | No. acc | Average (across the floor) |
|---|---|---|---|---|---|---|
| Andy_WL2_1 | 1 | 0,176 | 9 | 0,473 | 3 | 0,342 |
| Andy_WL2_2 | 1 | 0,117 | 8 | 0,454 | 10 | 0,291 |
| Georg_WL2_1 | 1 | 0,139 | 8 | 0,413 | 2 | 0,292 |
| Georg_WL2_2 | 1 | 0,136 | 7 | 0,376 | 10 | 0,254 |
| Ivan_WL2_1 | 1 | 0,224 | 8 | 0,813 | 2 | 0,517 |
| Ivan_WL2_2 | 1 | 0,251 | 8 | 0,765 | 6 | 0,537 |
| Jacin_WL2_1 | 1 | 0,086 | 9 | 0,496 | 11 | 0,334 |
| Jacin_WL2_2 | 1 | 0,247 | 8 | 0,581 | 4 | 0,472 |
| Matt_WL2_1 | 1 | 0,092 | 8 | 0,319 | 15 | 0,226 |
| Matt_WL2_2 | 1 | 0,126 | 8 | 0,408 | 4 | 0,271 |
| Matthias_WL2_1 | 1 | 0,302 | 8 | 0,700 | 4 | 0,537 |
| Matthias_WL2_2 | 1 | 0,239 | 8 | 0,893 | 11 | 0,543 |
| Michael_WL2_1 | 1 | 0,125 | 12 | 0,815 | 3 | 0,458 |
| Michael_WL2_2 | 1 | 0,187 | 8 | 0,860 | 3 | 0,136 |
| Miguel_WL2_1 | 1 | 0,090 | 7 | 0,229 | 2 | 0,163 |
| Miguel_WL2_2 | 1 | 0,082 | 8 | 0,326 | 14 | 0,191 |
| Pau_WL2_1 | 1 | 0,120 | 12 | 0,493 | 2 | 0,272 |
| Pau_WL2_2 | 1 | 0,044 | 13 | 0,297 | 11 | 0,191 |
| Yann_WL2_1 | 1 | 0,177 | 12 | 1,894 | 11 | 0,368 |
| Yann_WL2_2 | 1 | 0,202 | 12 | 0,530 | 5 | 0,333 |
| | | | | Average value Across the floor | | 0,336 |

In this case the total average $a_{w,rms}$ is 0,284 $m/s^2$. The average value for females is 0,231 $m/s^2$ and for males is 0,336 $m/s^2$.

- Toratti & Talja

  As the three results are higher than 0,12 $m/s^2$, they are classified as vibration class E which is the worst vibration class.

- ISO 2631-2:1989, t = 1s

  As for the fist walking line, the overall weighted acceleration values for the three cases exceed the highest of the residential limits. Again, the probability of adverse comments is high which is the same result then in the subjective test.

Another example of acceleration against the frequency is shown below this line.

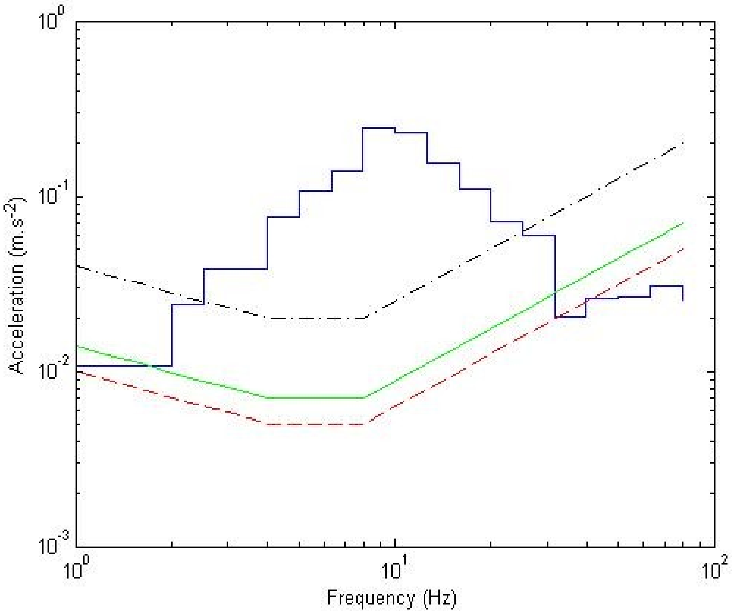


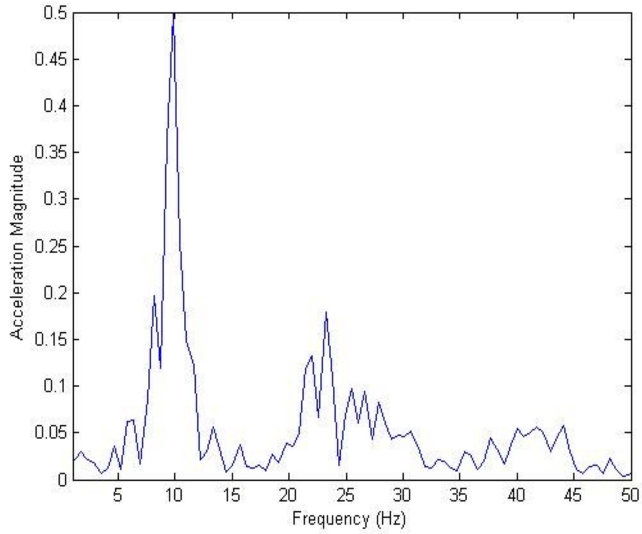

*Figure 7.4: Acceleration magnitudes in 1/3 octave bands with an averaging time of 1 second. The bottom line is the base curve of ISO 2631-2:1989. The line in the middle is the curve valid for residential for night time and the top one is the limit for day time.*

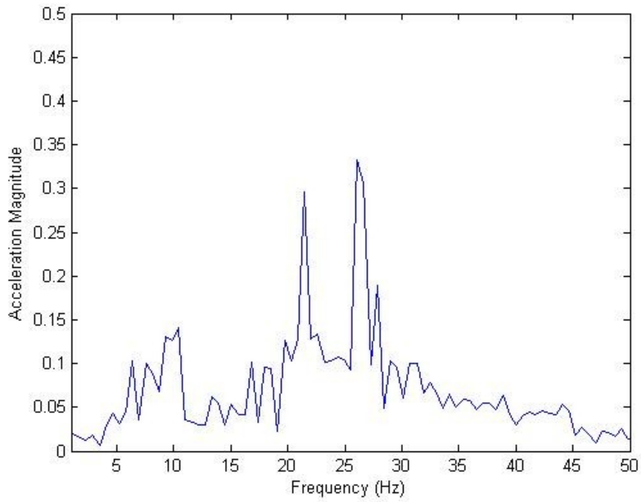
In this walking line the accelerometer that more times gave the minimum value was number 8. This was placed from where the volunteers were asked to start walking. On the other hand, the accelerometer number 3 gave the highest acceleration values more times than any other accelerometer on the floor.

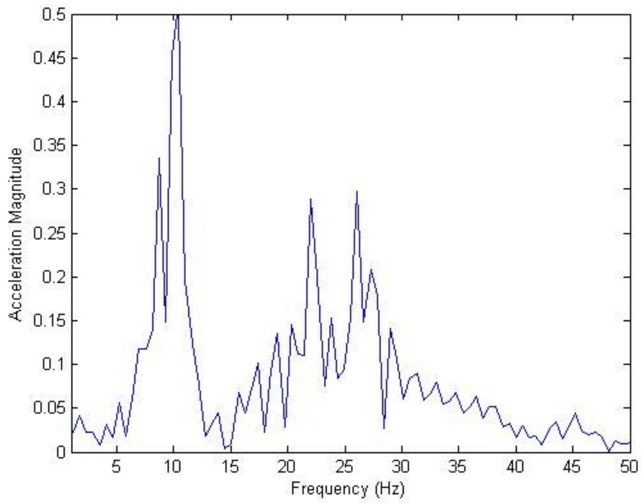
### 7.4.3 Natural Frequencies

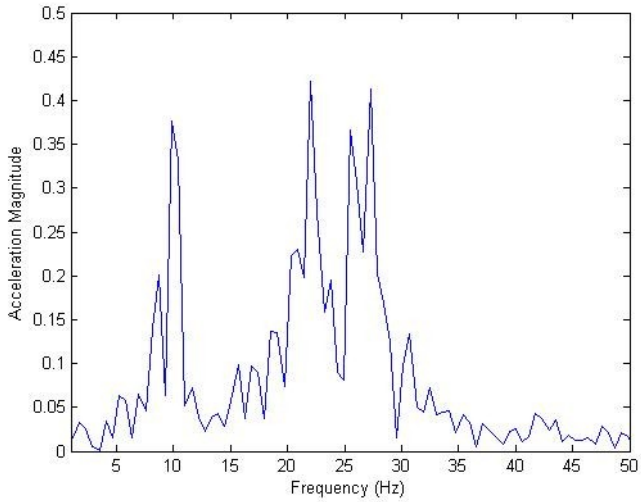
In the following diagrams the frequency against the acceleration magnitude are plotted in order to obtain the natural frequency values. As it is explained in section 3.1, the natural frequency values can be distinguished from the graphs due to the spikes. For this experiment only the lowest natural frequencies are of interest. As a result, the response spectrum has been limited to show frequencies between 0 and 50 Hz.

All the graphs come from different person but from the same accelerometer. This is accelerometer number 9 which is placed in the middle point of the floor.


Acceleration Magnitude
Frequency (Hz)


Acceleration Magnitude
Frequency (Hz)


Acceleration Magnitude
Frequency (Hz)




From the response spectra above, the following natural frequencies can be identified:

- $f_1$= 8 Hz
- $f_2$= 11 Hz
- $f_3$= 22 Hz
- $f_4$= 27 Hz

This results have been checked with a mathematical solution, see appendix 3. The results obtained from these calculations are the following:

- $f_1$= 10,59 Hz
- $f_2$= 42,2 Hz
- $f_3$= 95,1 Hz

One of the reasons of these differences between the two set of results could be the large amount of simplifications.

# 8 Discussion and Conclusion

The subjective test results showed up that an immense majority of the volunteers agreed that the experimental floor was unacceptable or absolutely unacceptable with regard to vibrations induced by another person. The two different walking lines have shown similar results when it comes to vibrations induced by another person; furthermore, meaning that the results were negative. Nevertheless, the first walking line obtained an slightly better result than the second walking line.

One of the reasons for this can be the distance between the chair and the walking line and the chair used in the experiment. This distance in the second walking line was on centimeter further away than in the first walking line. Also, in the first walking line, the chair was place over a supported beam. This could have reduced the vibrations intensity affecting the volunteer.

On the other hand, when the vibrations were induced by their own walking, the result turned up to be different between the two walking lines. Over half of the volunteers found the walking line two barely perceptible in terms of intensity of vibrations. As a result, the same amount of volunteers found the floor in this direction acceptable. A reason for such contrast in behavior could be the difference in the length of the spans, being much shorter for walking line two.

The differences between gender were quite significant. In all the cases women perceived less the vibrations than men. As a result, female rated the floor in both directions less annoying than female. The only possible reason for this result with the information obtained from the subjective test is the weight. As women usually are less heavy than men; thereby they cause smaller amplitudes of vibration. Also, light people are less sensitive to higher frequencies and more sensitive to lower frequencies than heavier people.

The results obtained in the direct measurements are in agreement with the results in the subjective test. The differences between the two walking lines are clearly seen from the results. The overall weighted acceleration average value for the first walking line was double than for the second one. Also, the differences between gender are clearly seen in the direct measurements results where the male obtained much higher values than female. All these obtained results were evaluated according to the method proposed by Talja and Toratti, and the former ISO standard 2631-2:1989. According to the Talja or Toratti method, all the overall average accelerations considered in the experiment were classified as vibration class E, meaning that the vibrations are without restrictions. Also, when the results were evaluated using the ISO standard mention above, the outcome was negative. Again, all the overall average accelerations were above the maximums proposed in this ISO standard.

The natural frequencies was another piece of information obtained in this thesis. Two different sources were used in order to obtain them. The first come from the direct measurements and the second was using mathematical calculations. Some differences between the two results can be appreciated. The answer for this can be the simplification of the mathematical model.

If further investigation is carried out, a finite element model could be made in order to increment the accuracy of the experimental floor behavior. Another way of improving the results could be done making more initial test with the accelerometers in order to spot more interesting location with regard to vibrations. Also, it would have been interesting to know how much the vibrations magnitudes will change if a larger floor was used,specially for the second walking line.

To sum up, this thesis shows that the simply supported experimental floor understudy is absolutely unacceptable with regard to vibration serviceability. As a result, there is a high risk of adverse comments. In order to use this floor in real constructions, the structure of it needs to be improve to get optimal performance.

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## Standards

Swedish Standard SS-ISO 2631-1:1997: *Vibration and shock-Evaluation of human exposure to whole-body vibration-Part 1: General requirements.*

ISO 2631-2:2003: *Vibration and shock-Evaluation of human exposure to whole-body vibration-Part 2 : Vibration in buildings (1 Hz to 80 Hz).*

ISO 2631-1:1985: *Evaluation of human exposure to whole-body vibration- Part 1: General requirements.*

ISO 2631-2:1989: *Evaluation of human exposure to whole-body vibration- Part 2: Continuous and shock-induced vibration in buildings (1 to 80 Hz).*

# Appendix 1: Questionnaire

## Questionnaire

Name:_______________________________________

Test person no.______

Male [ ]
Female [ ]

Age _____

Weight _____

### First Walking Line

#### Test 1: Rating of vibrations due to test person's own walking test 1

Walk on the floor structure and evaluate the vibration serviceability/performance of the floor.

1.1 Please, classify the ***intensity*** of the vibrations.

| | | | |
|---|---|---|---|
| Strongly perceptible | Clearly perceptible | Barely perceptible | Imperceptible |

1.2 Is the floor ***acceptable*** in a newly built house or flat?

| | | | |
|---|---|---|---|
| Absolutely unacceptable | Unacceptable | Acceptable | Absolutely acceptable |

1.3 On a scale from 1 to 10, rate the vibration serviceability/performance of the floor.

1 2 3 4 5 6 7 8 9 10
Very poor Very good

### Test 2: Rating of vibrations induced by a walking person.

Sit down on a chair placed on the floor structure and evaluate the vibration serviceability/performance of the floor when another person is walking by.

2.1 Please, classify the ***intensity*** of the vibrations.

| | | | |
|---|---|---|---|
| Strongly perceptible | Clearly perceptible | Barely perceptible | Imperceptible |

2.2 Is the floor ***acceptable*** in a newly built house or flat?

| | | | |
|---|---|---|---|
| Absolutely unacceptable | Unacceptable | Acceptable | Absolutely acceptable |

2.3 On a scale from 1 to 10, rate the vibration serviceability/performance of the floor.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Very poor | | | | | | | | | Very good |

## Second Walking Line

### Test 1: Rating of vibrations due to test person's own walking.

Walk on the floor structure and evaluate the vibration serviceability/performance of the floor.

1.1 Please, classify the ***intensity*** of the vibrations.

| | | | |
|---|---|---|---|
| Strongly perceptible | Clearly perceptible | Barely perceptible | Imperceptible |

1.2 Is the floor ***acceptable*** in a newly built house or flat?

| | | | |
|---|---|---|---|
| Absolutely unacceptable | Unacceptable | Acceptable | Absolutely acceptable |

1.3 On a scale from 1 to 10, rate the vibration serviceability/performance of the floor.

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|
| Very poor | | | | | | | | | Very good |

**Test 2: Rating of vibrations induced by a walking person.**

Sit down on a chair placed on the floor structure and evaluate the vibration serviceability/performance of the floor when another person is walking by.

2.1 Please, classify the ***intensity*** of the vibrations.

| | | | |
|---|---|---|---|
| Strongly perceptible | Clearly perceptible | Barely perceptible | Imperceptible |

2.2 Is the floor ***acceptable*** in a newly built house or flat?

| | | | |
|---|---|---|---|
| Absolutely unacceptable | Unacceptable | Acceptable | Absolutely acceptable |

2.3 On a scale from 1 to 10, rate the vibration serviceability/performance of the floor.

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|
| Very poor | | | | | | | | | Very good |

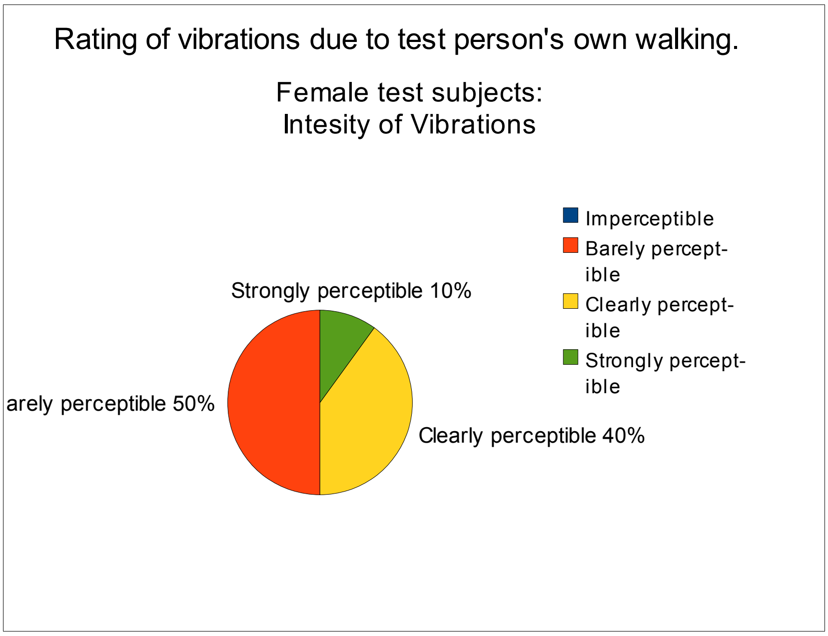
**Thank you for participating!**

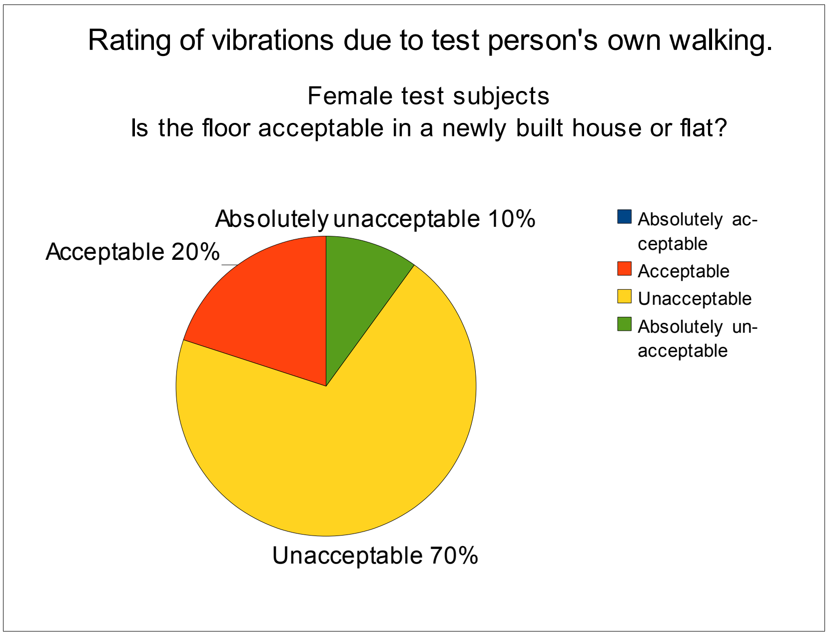
If you have anything to add, please write it below:

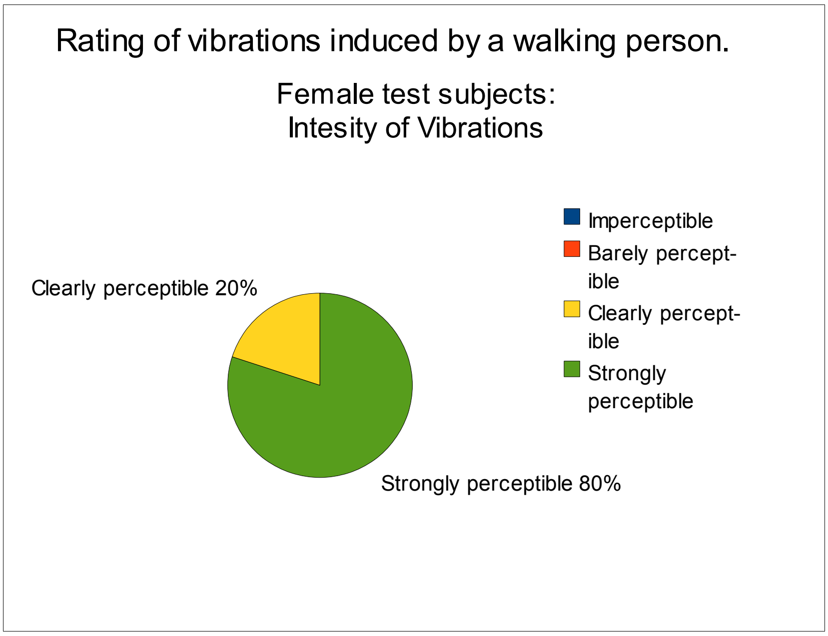
# Appendix 2: Subjective Test Results

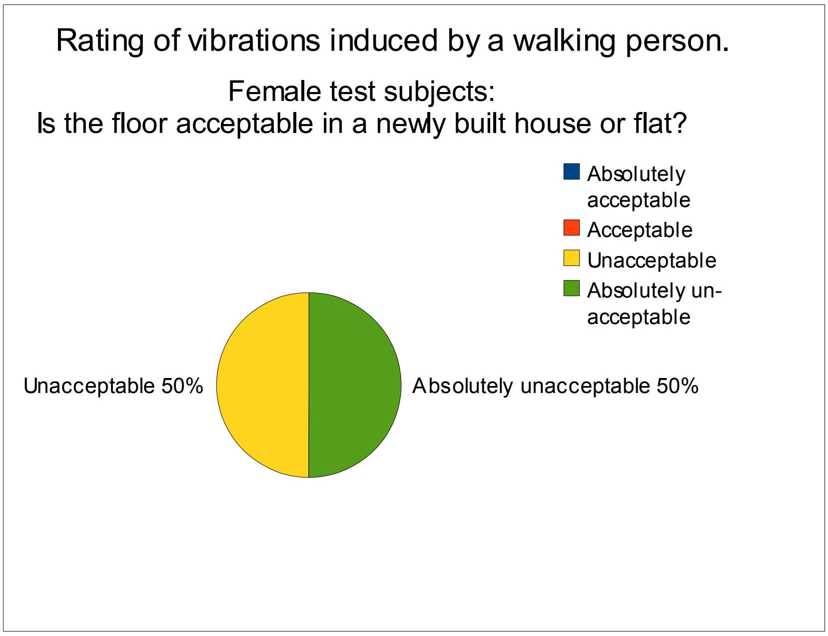
### Female test persons

- **Test 1:**

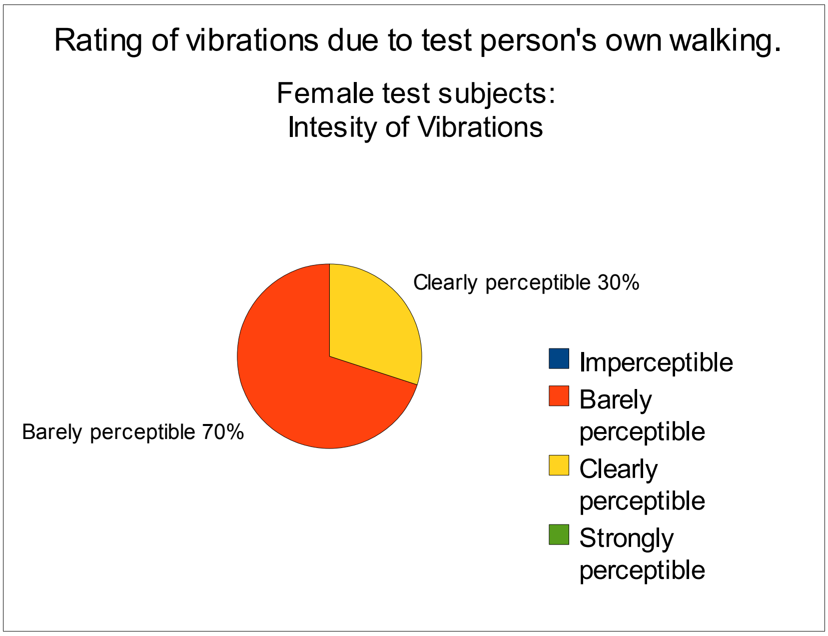


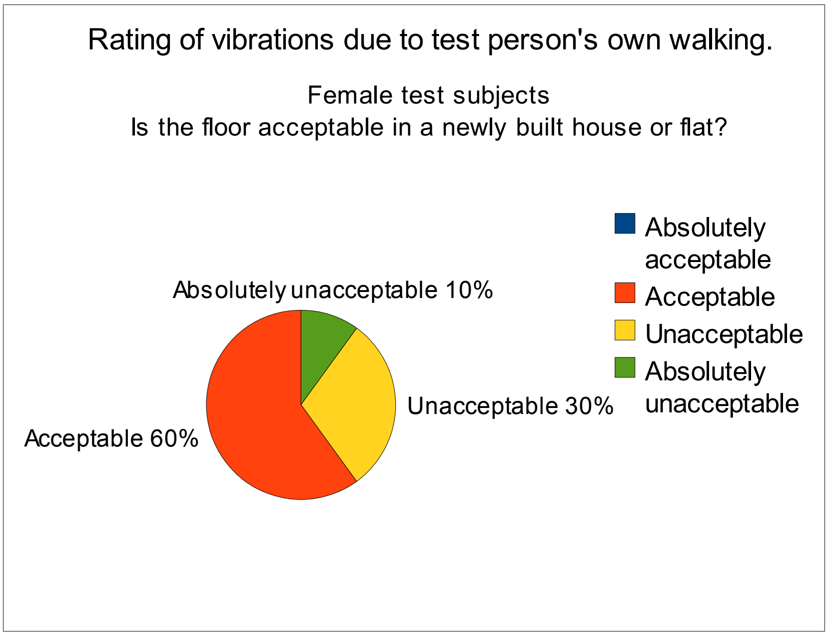



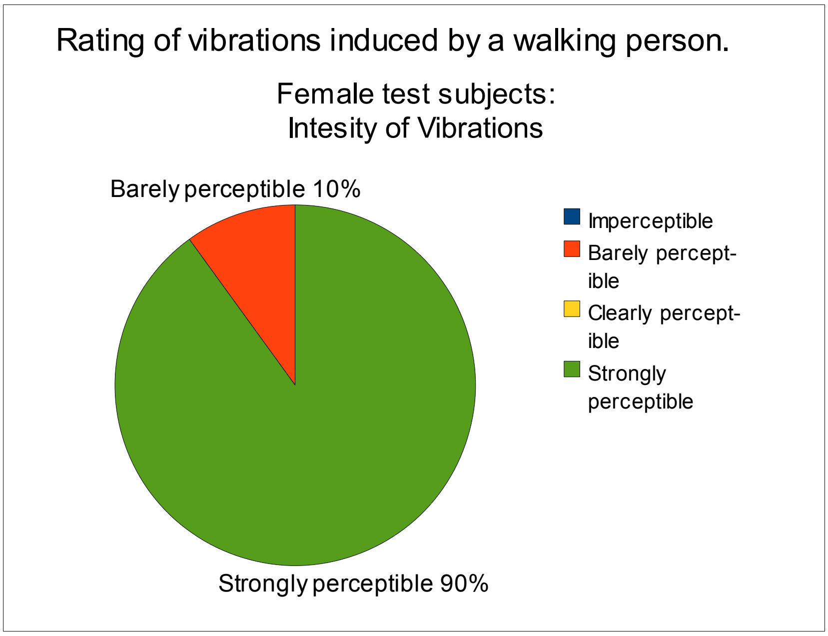

Rating of vibrations induced by a walking person.
Female test subjects:
Intesity of Vibrations
Imperceptible
Barely perceptible
Clearly perceptible
Strongly perceptible
Clearly perceptible 20%
Strongly perceptible 80%

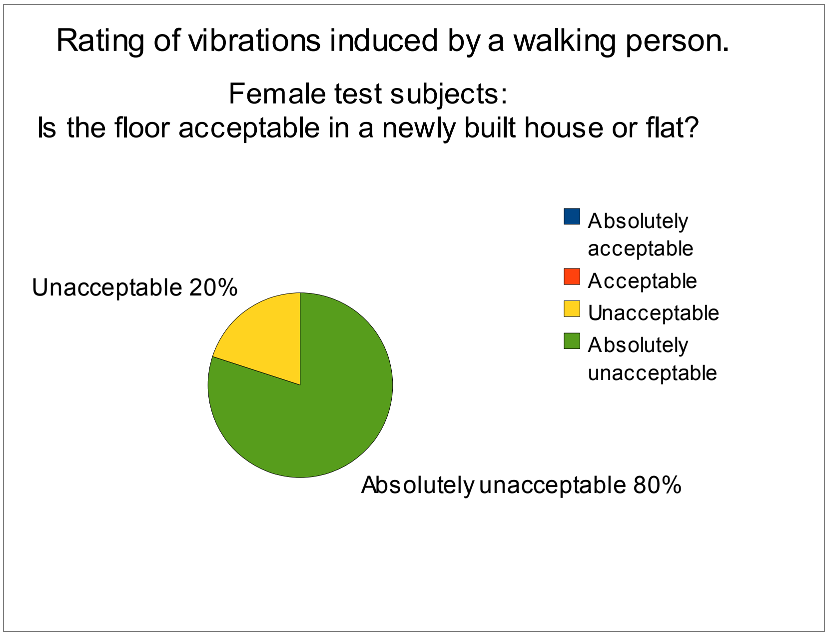

Rating of vibrations induced by a walking person.
Female test subjects:
Is the floor acceptable in a newly built house or flat?
Absolutely acceptable
Acceptable
Unacceptable
Absolutely unacceptable
Unacceptable 50%
Absolutely unacceptable 50%

- **Test 2:**


Rating of vibrations due to test person's own walking.
Female test subjects:
Intesity of Vibrations
Clearly perceptible 30%
Barely perceptible 70%
Imperceptible
Barely perceptible
Clearly perceptible
Strongly perceptible

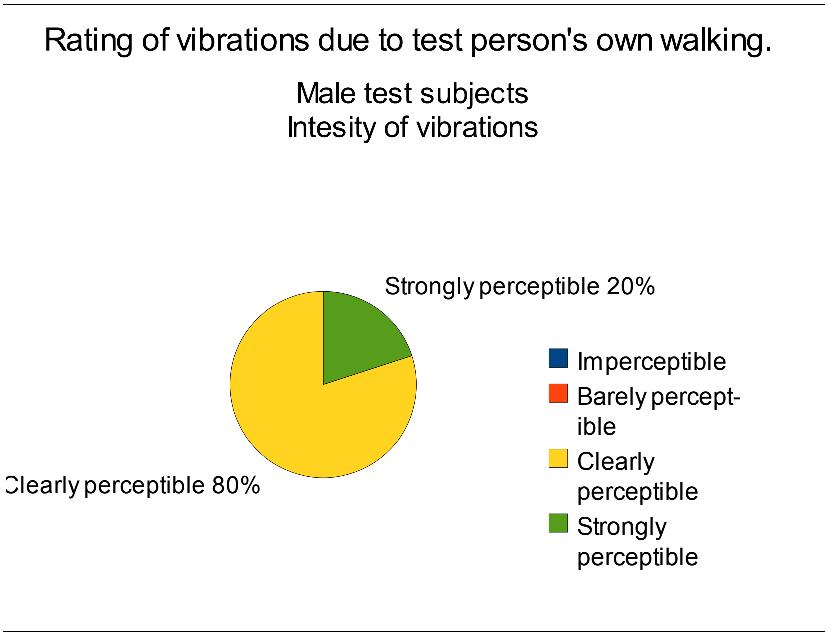

Rating of vibrations due to test person's own walking.
Female test subjects
Is the floor acceptable in a newly built house or flat?
Absolutely unacceptable 10%
Unacceptable 30%
Acceptable 60%
Absolutely acceptable
Acceptable
Unacceptable
Absolutely unacceptable

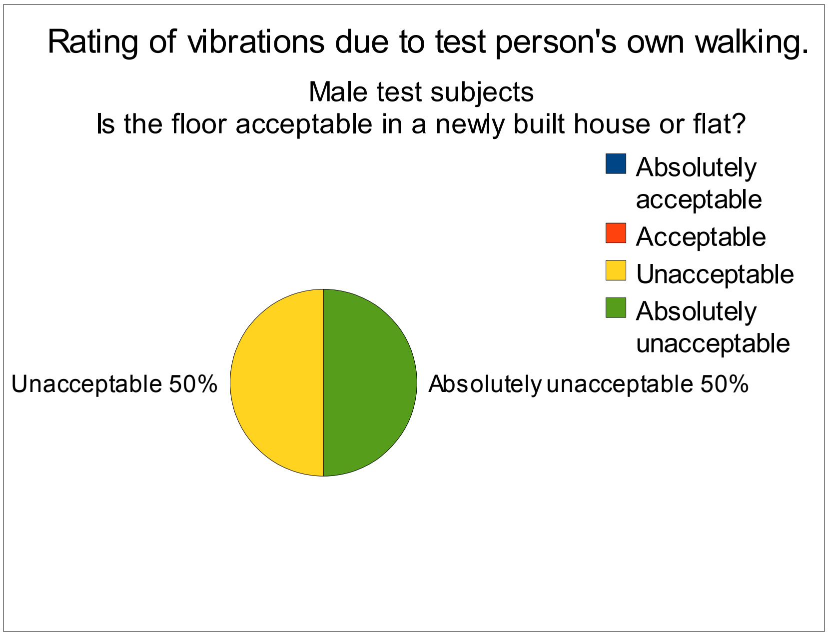

Rating of vibrations induced by a walking person.
Female test subjects:
Intesity of Vibrations
Barely perceptible 10%
Strongly perceptible 90%
Imperceptible
Barely perceptible
Clearly perceptible
Strongly perceptible

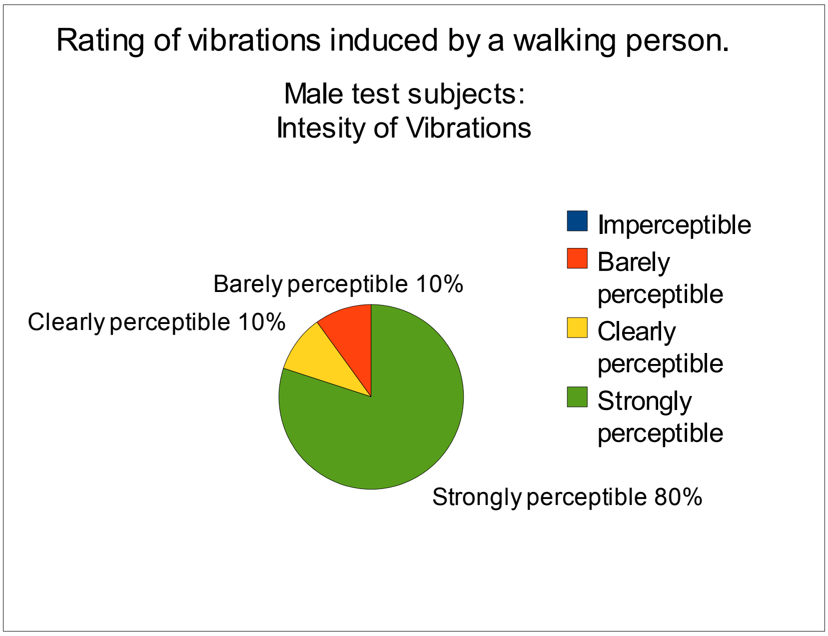

Rating of vibrations induced by a walking person.
Female test subjects:
Is the floor acceptable in a newly built house or flat?
Unacceptable 20%
Absolutely unacceptable 80%
Absolutely acceptable
Acceptable
Unacceptable
Absolutely unacceptable

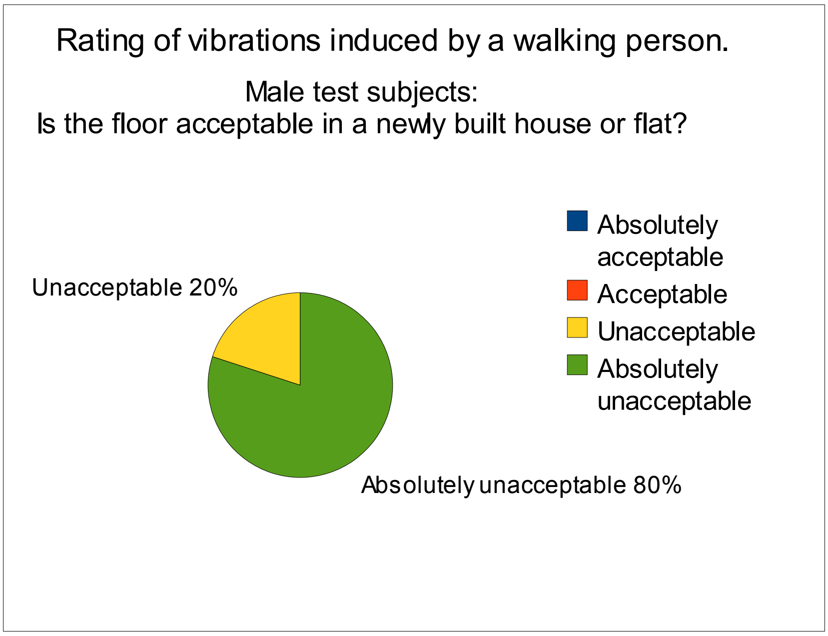
**Male test persons**

- **Test 1:**

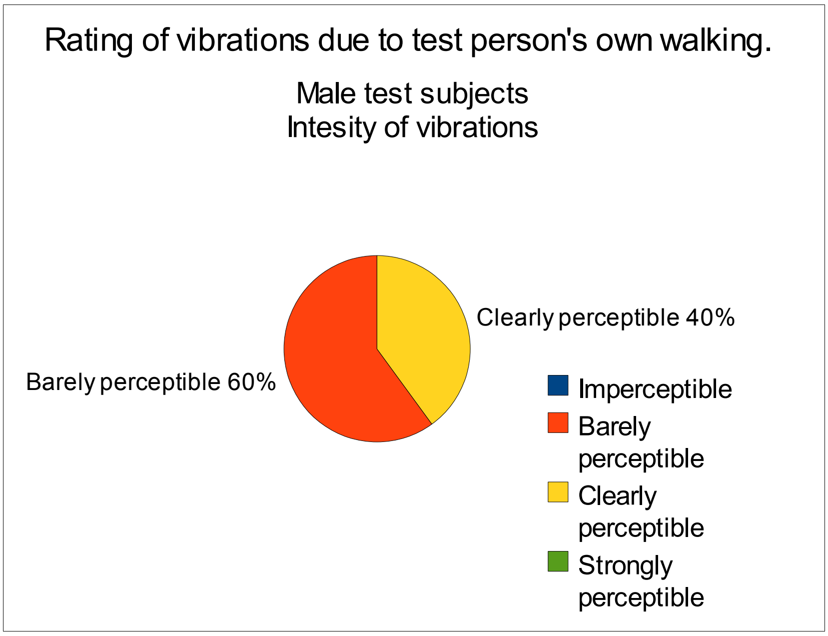


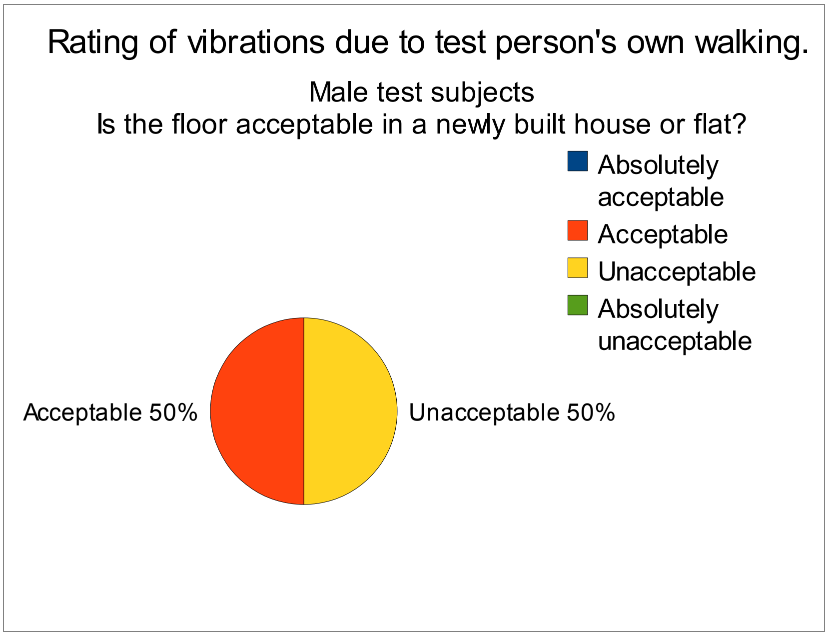



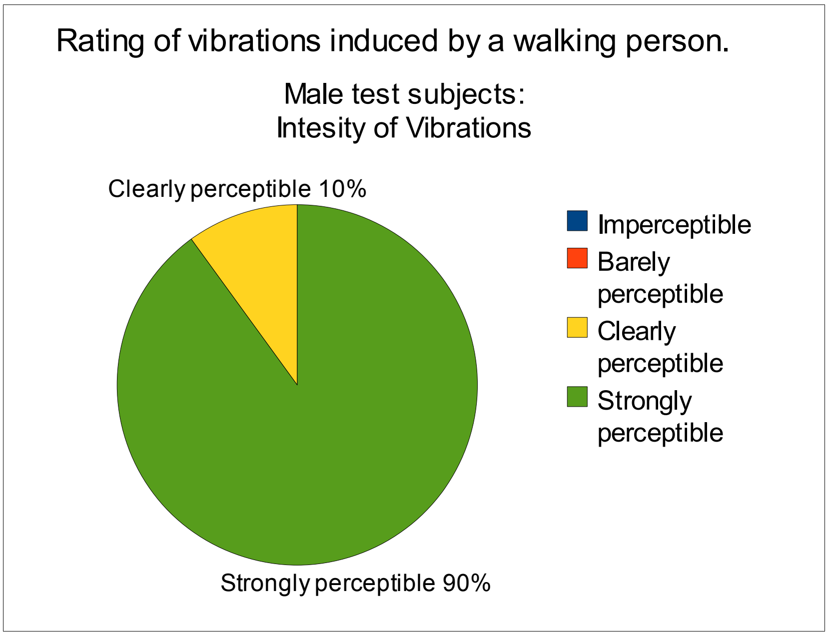

Rating of vibrations induced by a walking person.
Male test subjects:
Intesity of Vibrations
Imperceptible
Barely perceptible
Clearly perceptible
Strongly perceptible
Barely perceptible 10%
Clearly perceptible 10%
Strongly perceptible 80%

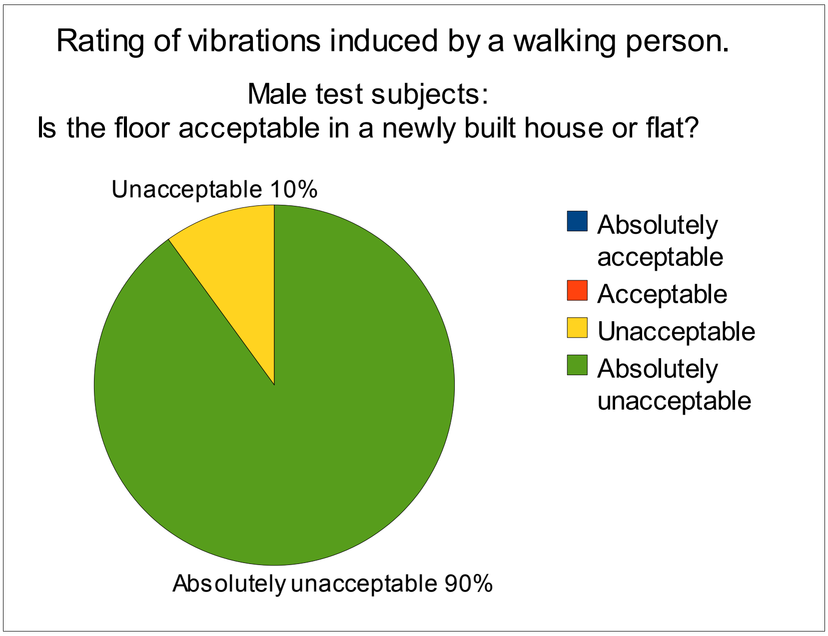

Rating of vibrations induced by a walking person.
Male test subjects:
Is the floor acceptable in a newly built house or flat?
Absolutely acceptable
Acceptable
Unacceptable
Absolutely unacceptable
Unacceptable 20%
Absolutely unacceptable 80%

- **Test 2:**


Rating of vibrations due to test person's own walking.
Male test subjects
Intesity of vibrations
Clearly perceptible 40%
Barely perceptible 60%
Imperceptible
Barely perceptible
Clearly perceptible
Strongly perceptible


Rating of vibrations due to test person's own walking.
Male test subjects
Is the floor acceptable in a newly built house or flat?
Absolutely acceptable
Acceptable
Unacceptable
Absolutely unacceptable
Acceptable 50%
Unacceptable 50%


Rating of vibrations induced by a walking person.
Male test subjects:
Intesity of Vibrations
Clearly perceptible 10%
Strongly perceptible 90%
Imperceptible
Barely perceptible
Clearly perceptible
Strongly perceptible


Rating of vibrations induced by a walking person.
Male test subjects:
Is the floor acceptable in a newly built house or flat?
Unacceptable 10%
Absolutely unacceptable 90%
Absolutely acceptable
Acceptable
Unacceptable
Absolutely unacceptable

# Appendix 3: Mathematical solution for the Natural Frequencies

The floor was assumed to be simple supported. As it is shown in the sketch below, this supports were placed in the longest sides.

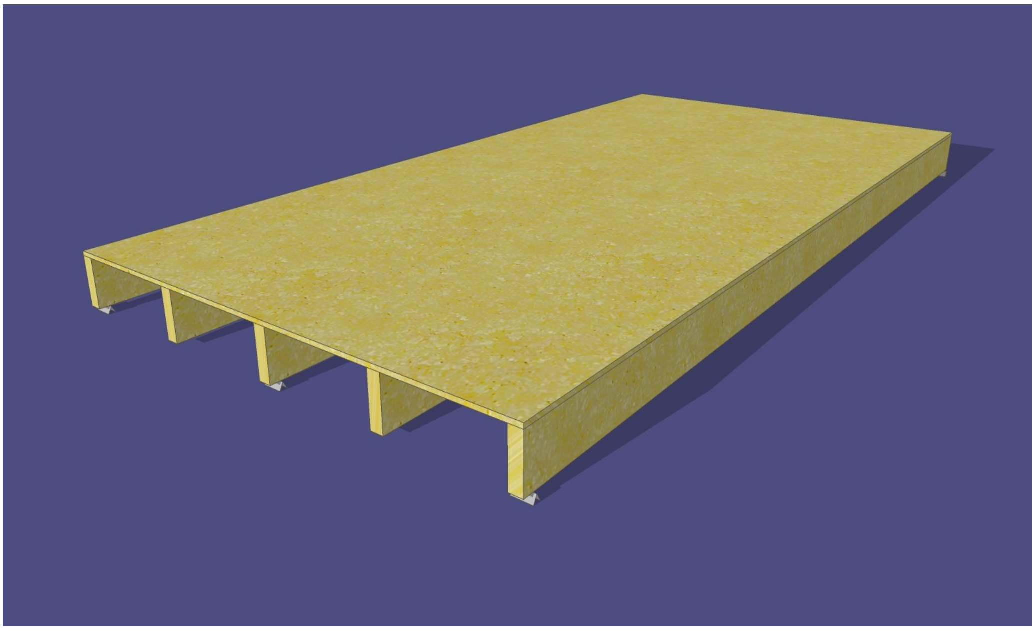


*Figure 1: 3-D model of the experimental floor.*

In order to obtain the natural frequencies form this floor some simplifications are needed. First of all, the floor will be treat as a simple supported beam, as it is shown in figure 2. Due to both sides of the beam are the same size, only one side has been considered. Finally, the beams that are not supported has not been taken into account.

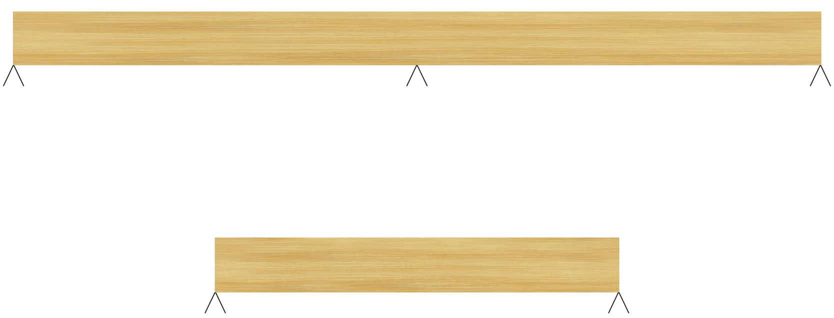


*Illustration 1: Final case considered for the natural frequency calculations.*

**Step calculations used:**

- Step 1: Wave number

$$K_n = n \cdot \Pi / L$$

Where $K_n$ is the wave number , n =1, 2, 3.... and L is the length between supports;

- Step 2: Angular frequency

$$W_n = \sqrt{\frac{B}{\rho \cdot S}} \cdot K_n^2$$

$$W_n = \sqrt{\frac{B}{\rho \cdot S}} \cdot \frac{n^2 \cdot \Pi^2}{L^2}$$

Where the bending stiffness is $B = E \cdot I = E \cdot \frac{w \cdot h^3}{12}$ , E is the young´s modulus and I is the second moment of inertia.
S is the cross-sectional area and ρ is the density.

- Step 3: Natural frequency

$$f_n = \frac{w_n}{2\Pi} = \sqrt{\frac{B}{\rho \cdot S}} \cdot \frac{n^2 \cdot \Pi}{2\mathrm{L}^2}$$

Where is $f_n$ is the n:th natural frequency.

The characteristics considered in for this floor are the following:

L= 1.2 m
w = 4.8 m
ρ = 600 kg/m$^3$
E = 3 Gpa
h = 0.015 m

**Results:**

- For n = 1 → $f_n$ = 10.59 Hz
- For n = 2 → $f_n$ = 42.2 Hz
- For n = 3 → $f_n$ = 95.1 Hz